Hadron Suppression in DIS @HERMES

Pasquale Di Nezza

(on behalf of the HERMES Collaboration)

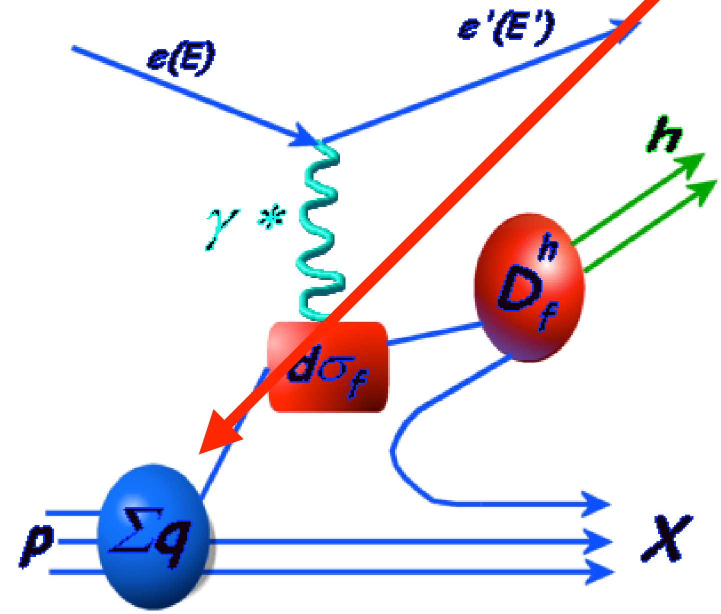
INFN Frascati

- DF and FF modification in a nuclear medium
- Nuclear attenuation measurements at HERMES
- Comparison with theory
- Hadron re-interaction vs partonic energy loss

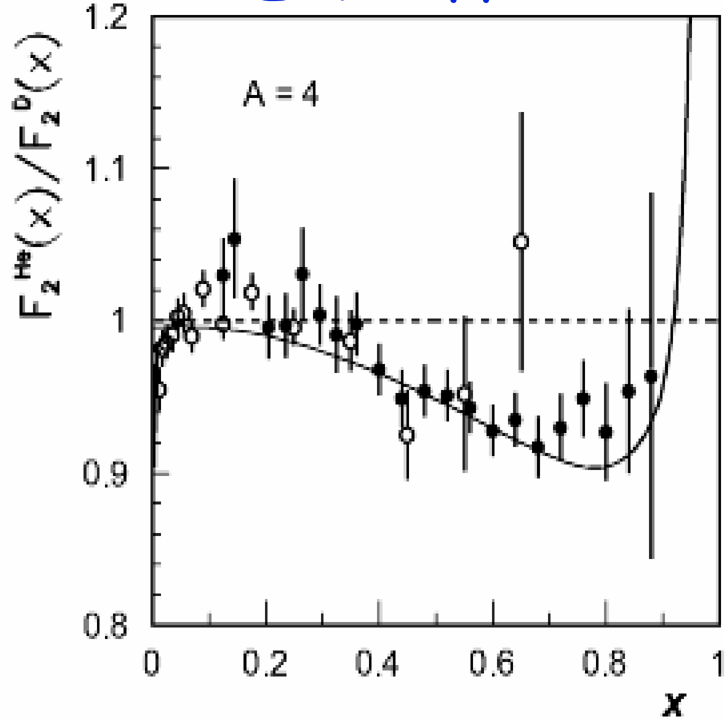
Quark and Matter, Oakland Jan 11-17, 2004

DF and FF on Nucleon & Nuclear Medium

$$d\sigma^{h}(z) \propto \sum_{f} q_f(x)\, d\sigma_f\, D_f^h(z)$$



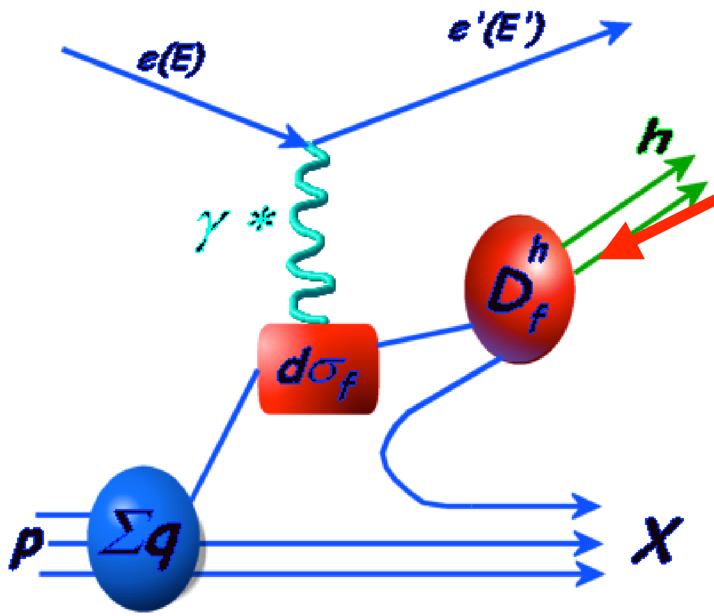
Inclusive DIS on nuclei:
EMC effect



Interpretation at both hadronic (nucleon's binding, Fermi motion, pions) and partonic levels (rescaling, multi-quark system)

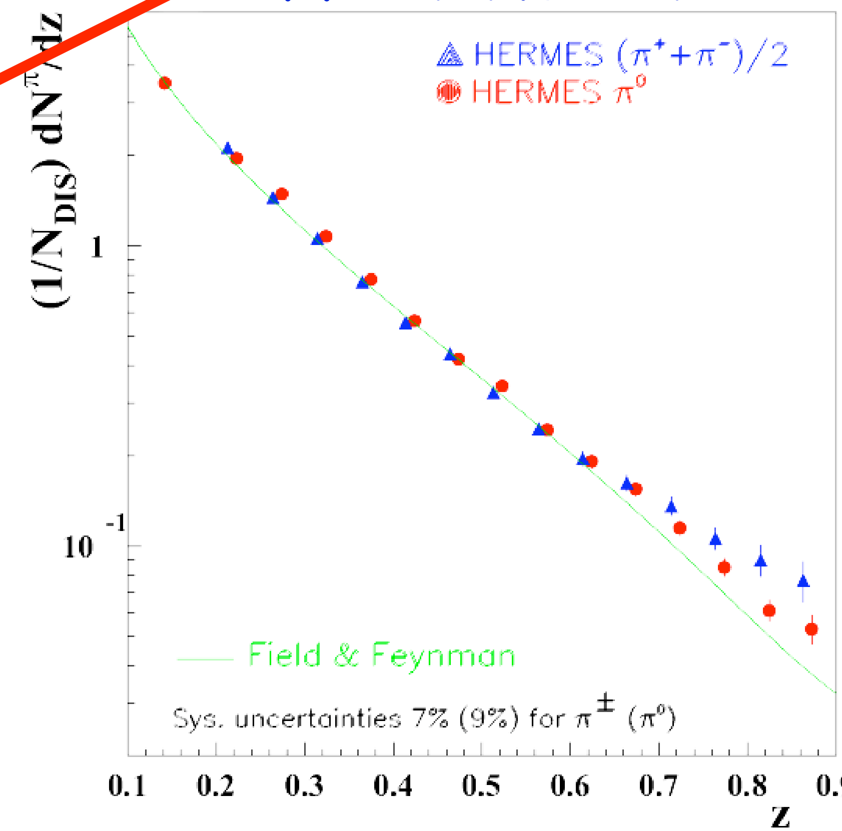
DF and FF on Nucleon & Nuclear Medium

$$d\sigma^{h}(z) \quad \sum_{f} q_f(x) \quad d\sigma_f \quad D_f^h(z)$$



z = E_h/í

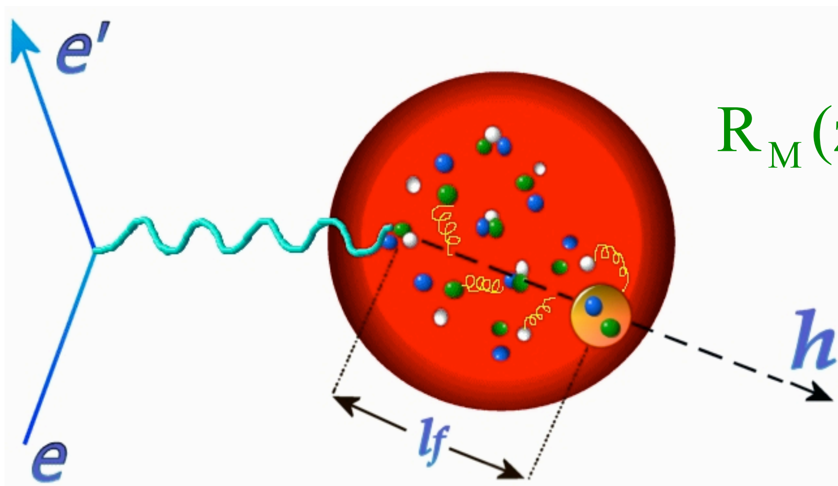
FF on nucleon:



FFs are measured with good precision and follow pQCD evolution like DFs (HERMES: EPJ C21(2001) 599). What happens in a nuclear medium ?

Nuclear Attenuation

Observation: reduction of multiplicity of fast hadrons due to both *hard partonic* and *soft hadron interaction.*



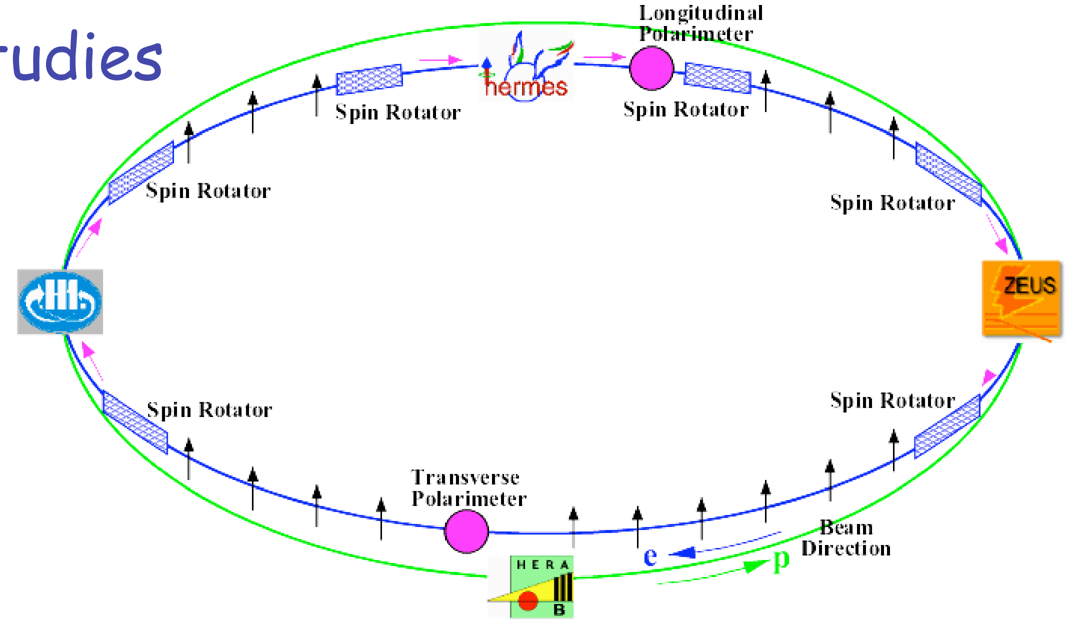
$$R_M(z,\nu) = \frac{\left.\frac{1}{\sigma_{DIS}}\frac{d^2\sigma_h}{dz\,d\nu}\right|_A}{\left.\frac{1}{\sigma_{DIS}}\frac{d^2\sigma_h}{dz\,d\nu}\right|_D} = \frac{\left.\frac{\Sigma e_f^2 q_f(x) D_f^h(z)}{\Sigma e_f^2 q_f(x)}\right|_A}{\left.\frac{\Sigma e_f^2 q_f(x) D_f^h(z)}{\Sigma e_f^2 q_f(x)}\right|_D}$$

Production and Formation Time measurements + FFs are crucial for the understanding of the space-time evolution of the hadron formation process hermes

- The energy range is well suited to study quark propagation and hadronization
- Measurements over the full z range
- Possibility to use several different gas targets
- PId: π^+, π^-, π^0, K^+, K^-, p, $\bar{p}$

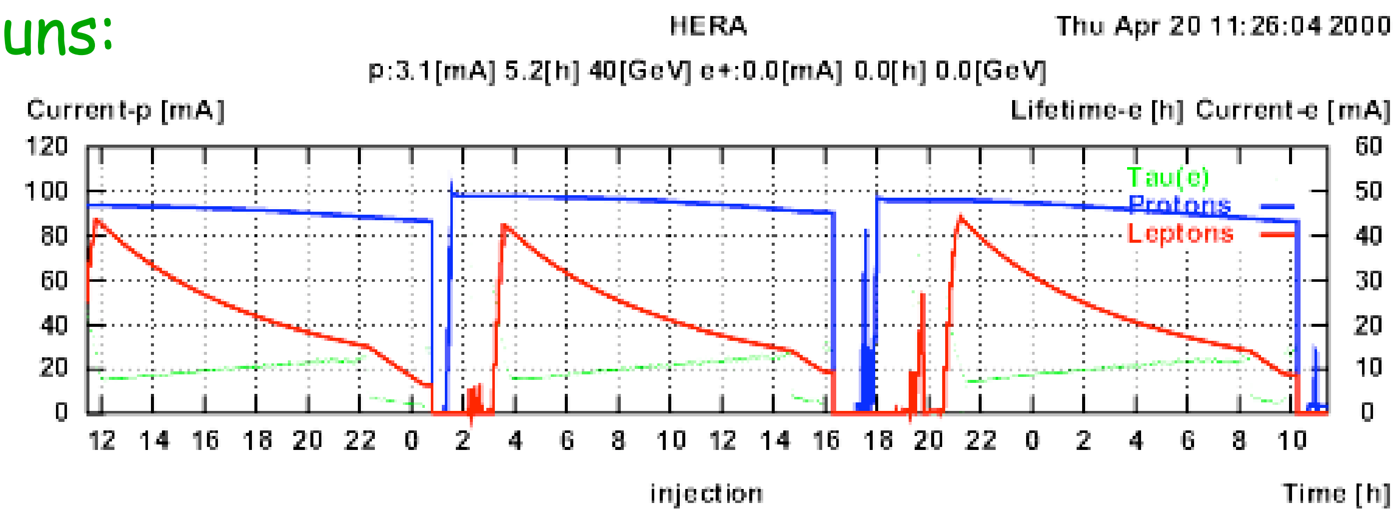
HERMES @ DESY

It is an experiment which studies the spin structure of the nucleon … and not only …



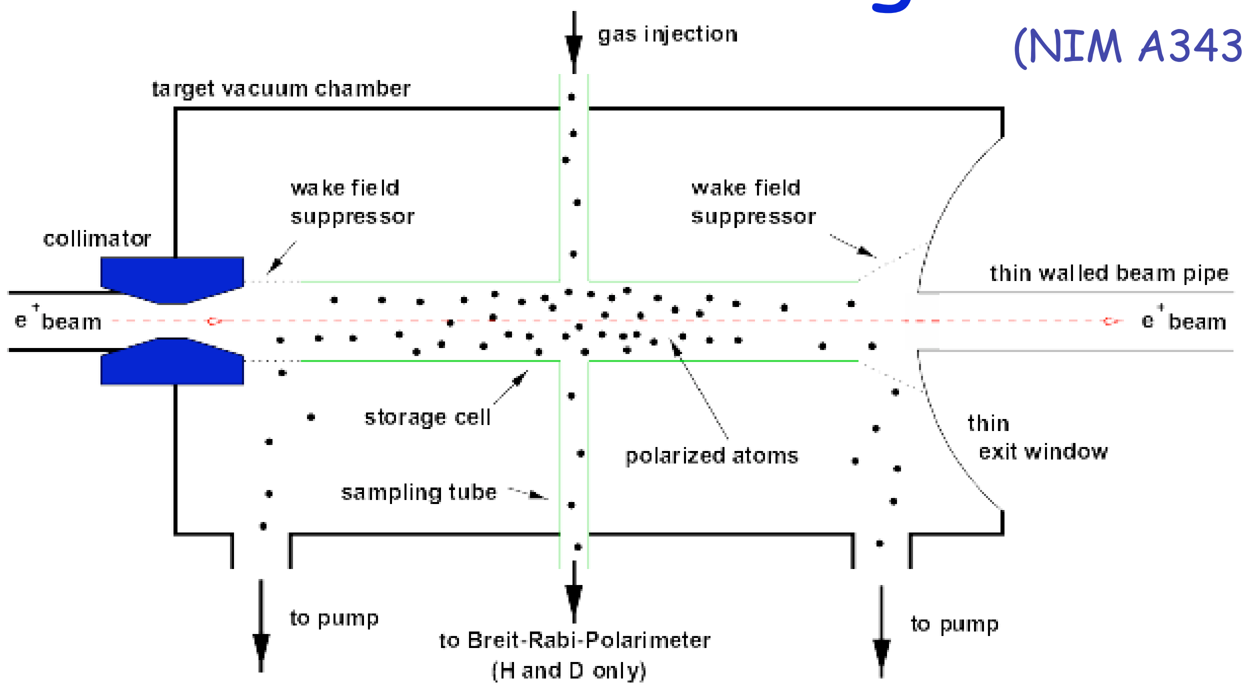
• 27.5 GeV e+, I_e~40 mA

Last part of the fill dedicated to high-density unpolarised target runs:



The Internal Target

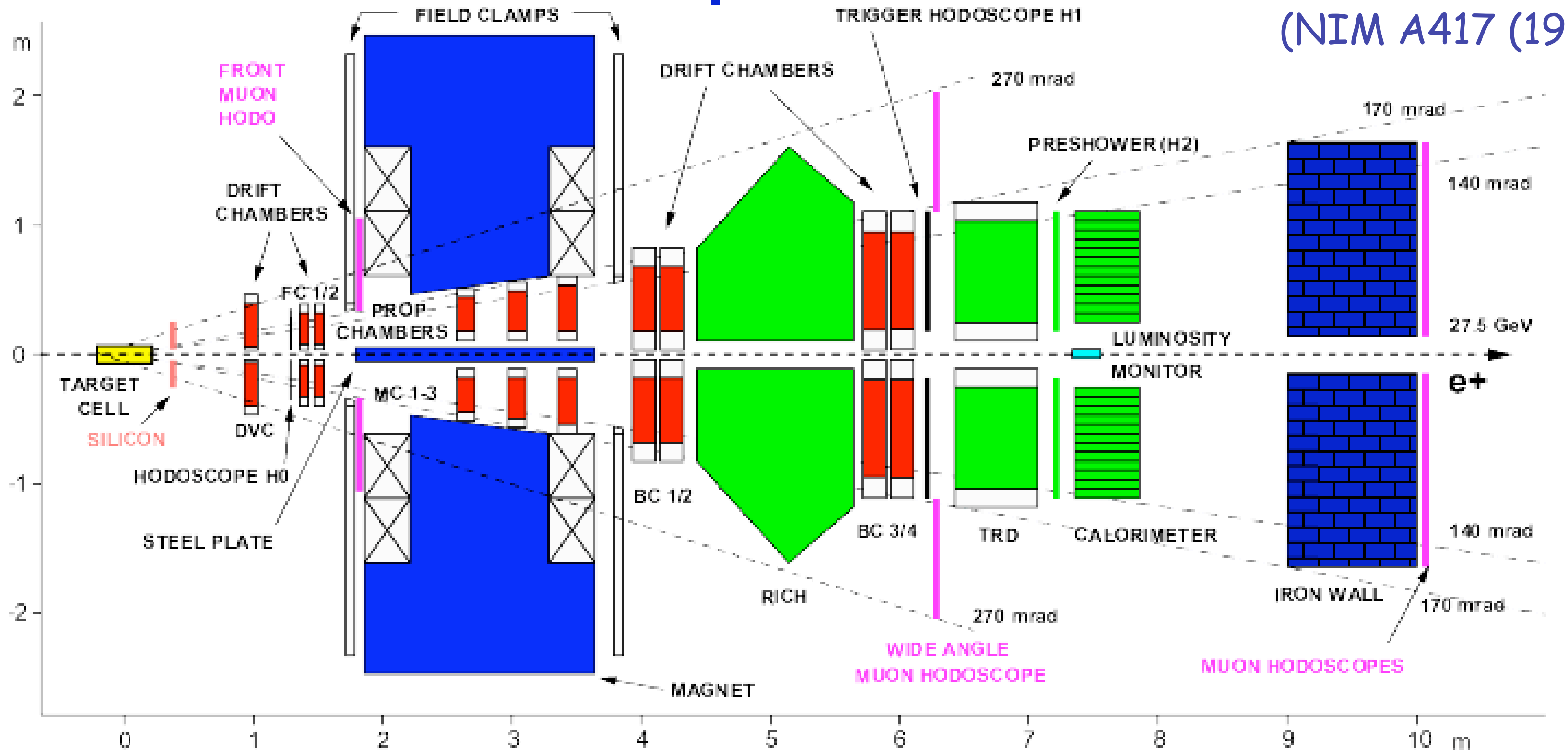
(NIM A343 (1994) 334)



- Internal storage cell
- Pure gas target, no dilution factor
- Nuclear targets: (H, D), ^{3}He, ^{4}He, ^{14}N, ^{20}Ne, ^{40}Ar, ^{84}Kr, ^{131}Xe
- Densities: ~10^{15} – 10^{17} nucl*cm^{-2}

The Spectrometer

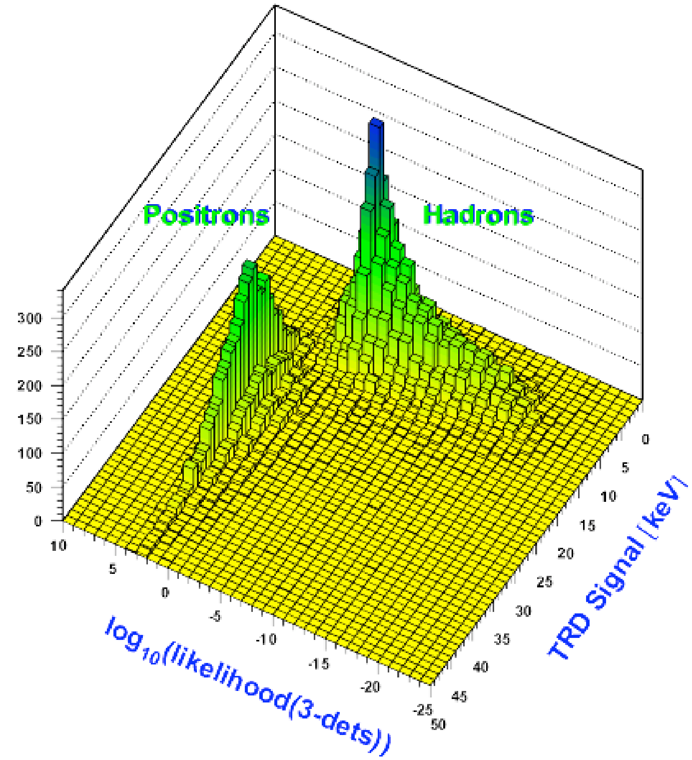
(NIM A417 (1998) 230)

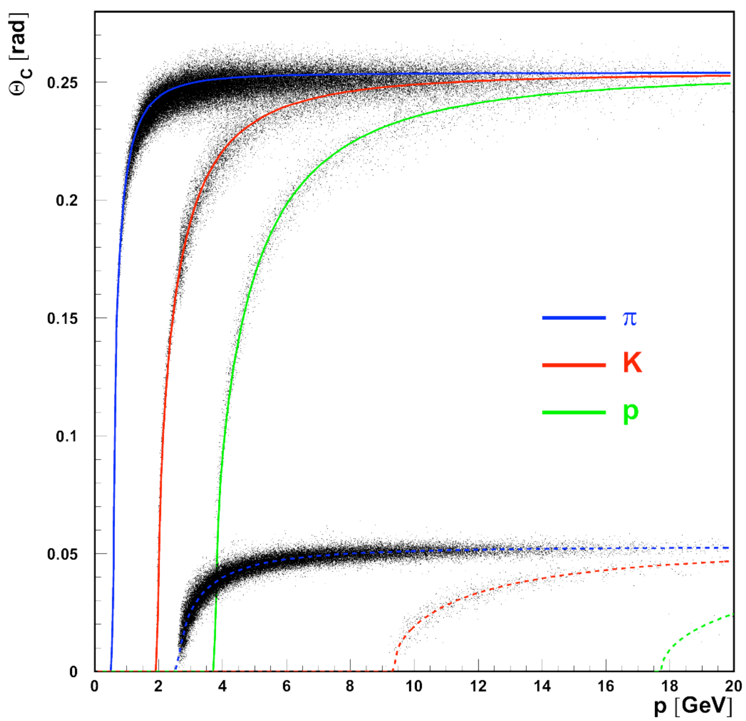


- e+ identification: 99% efficiency and <1% of contamination
- PID: RICH, TRD, Preshower, e.m. Calorimeter
- For N target: by Cerenkov pion ID in the range 4<p<14 GeV
- For He, Ne, Kr target: by RICH , K, p ID in the range 2.5<p<15 GeV

Particle Identification

Positron – hadrons separation:

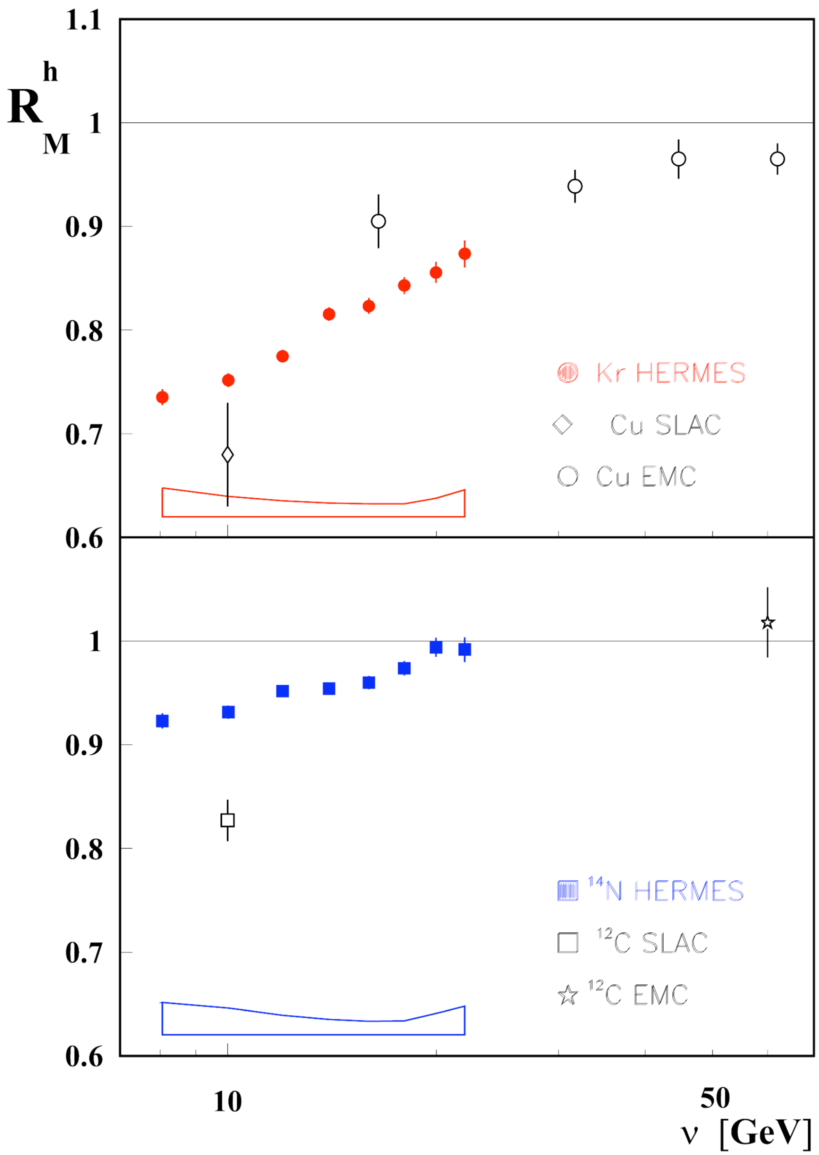




Double radiator RICH: Aerogel + C_4F_{10}. Cerenkov photons detected by ~4000 PMTs.

Detection efficiency: 99% (□), 90% (K), 85-95% (p)

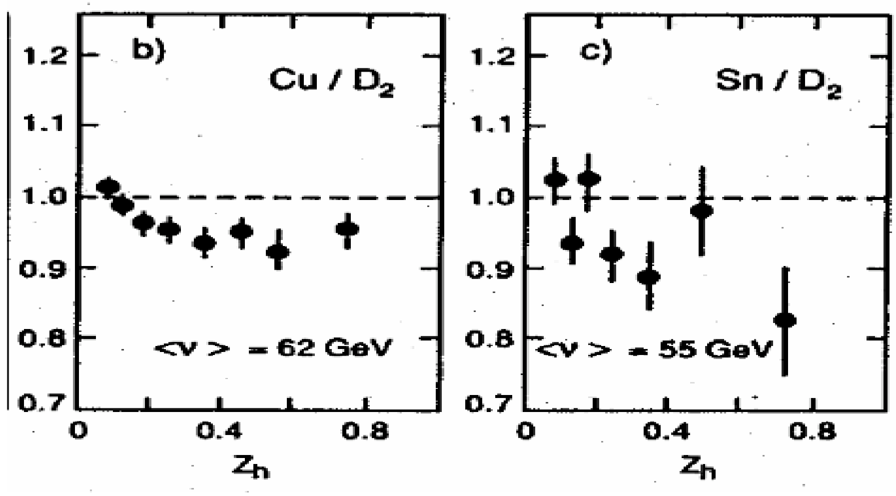
Hadron Attenuation



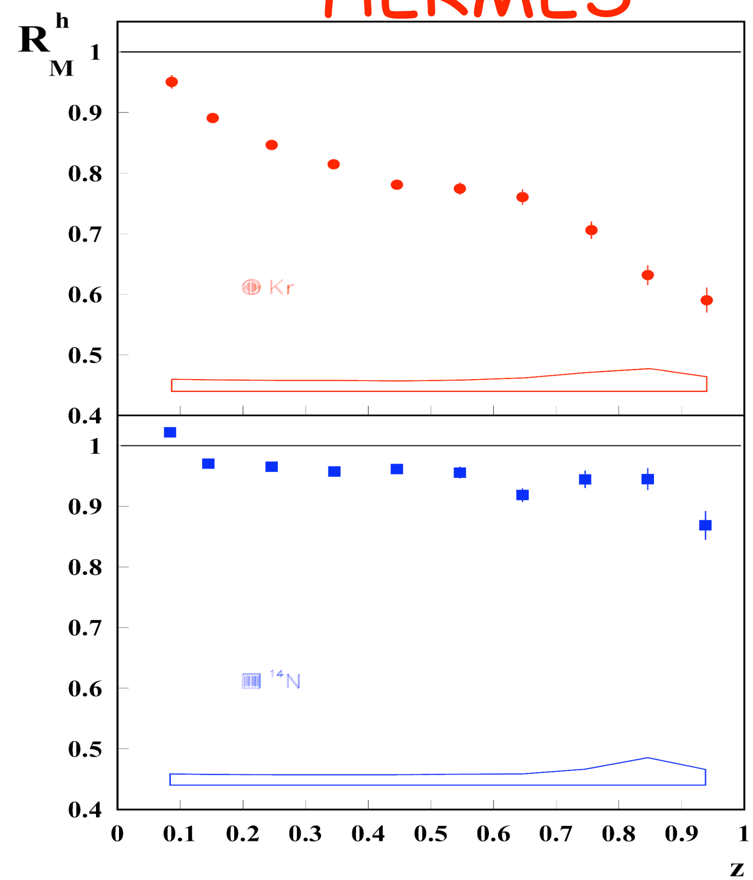
- Clear nuclear attenuation effect
- Increase with ν consistent with EMC data at higher energy
- Discrepancy with SLAC due to the *EMC effect*, not taken into account at that time
- HERMES kinematics is well suited to study quark propagation and hadronization

Hadron Attenuation

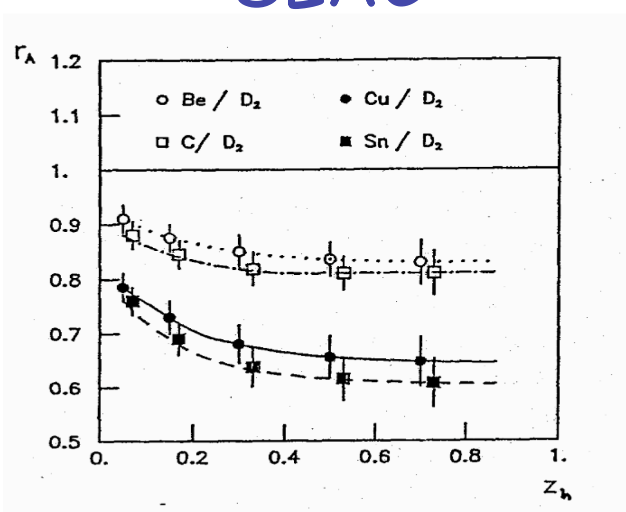
EMC



HERMES



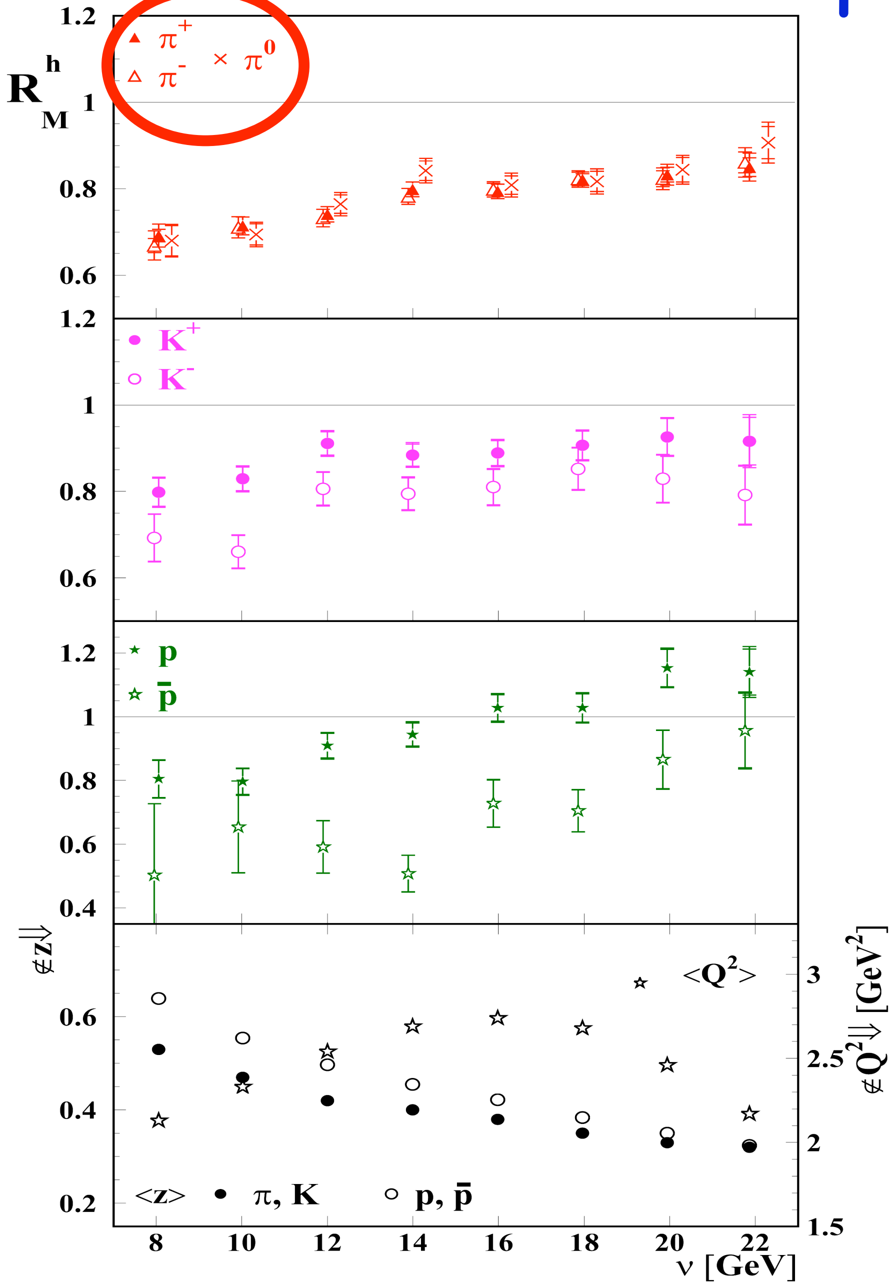
SLAC



- Significant attenuation of fast forward hadrons
- HERMES data provide information in the unexplored region z>0.8

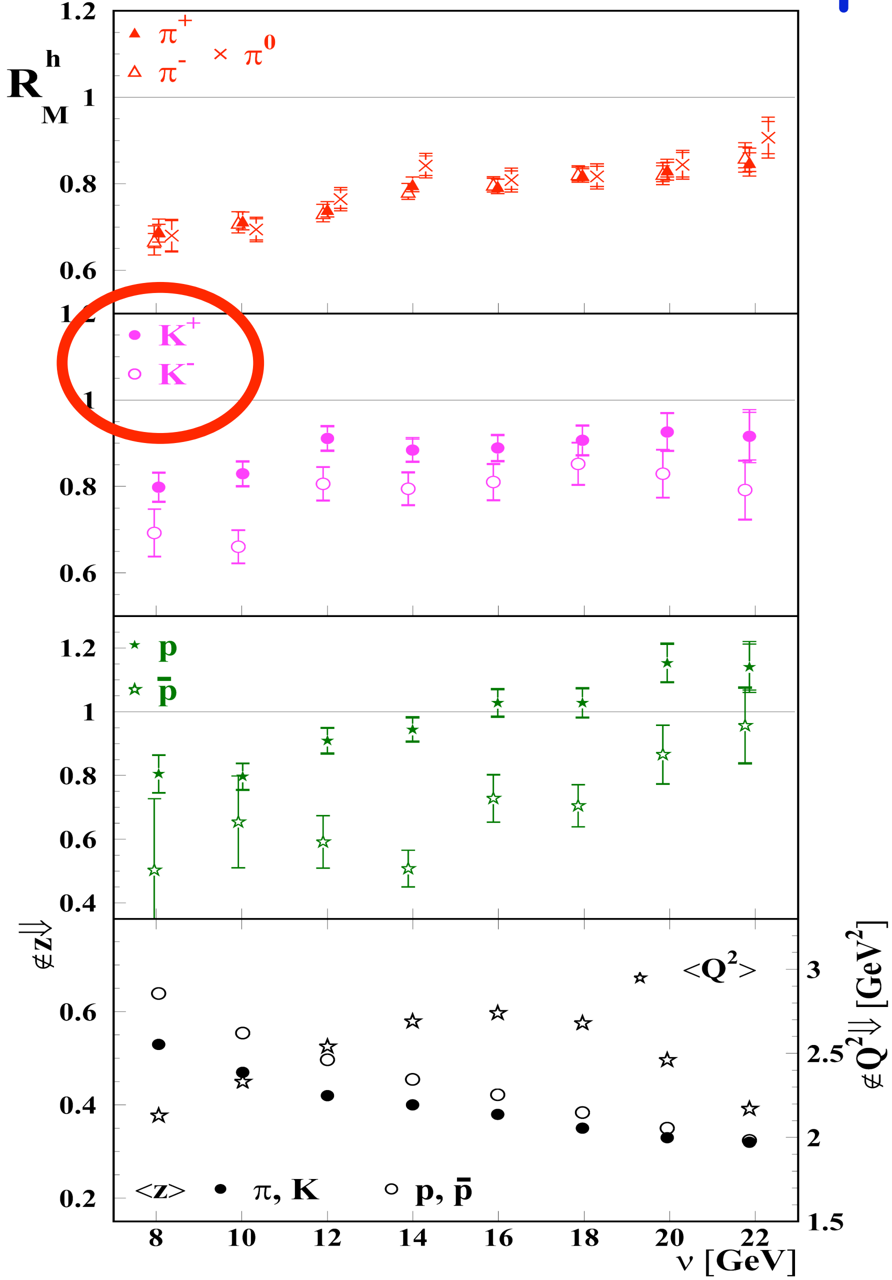
Hadron separation vs □

HERMES, PLB 577 (2003) 37



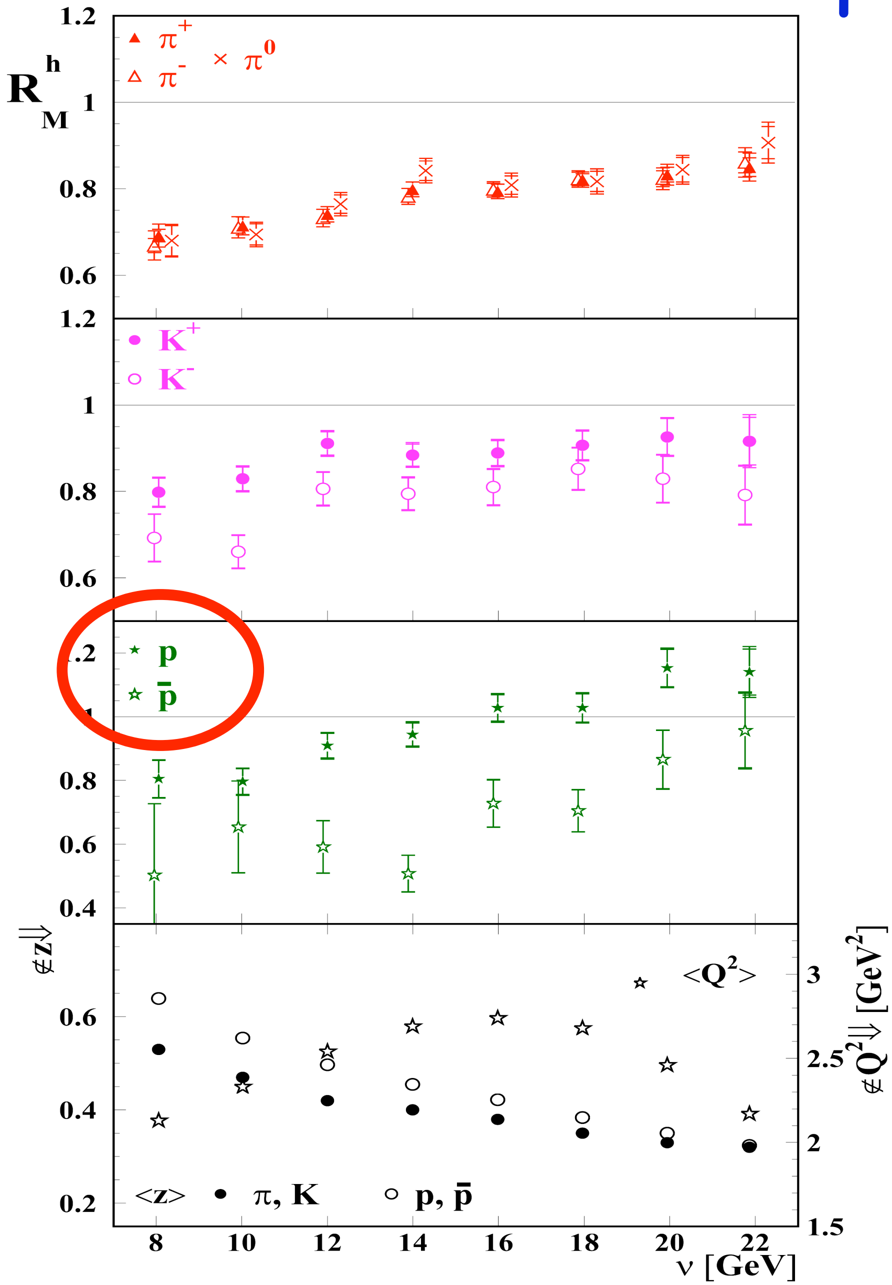
Hadron separation vs

HERMES, PLB 577 (2003) 37



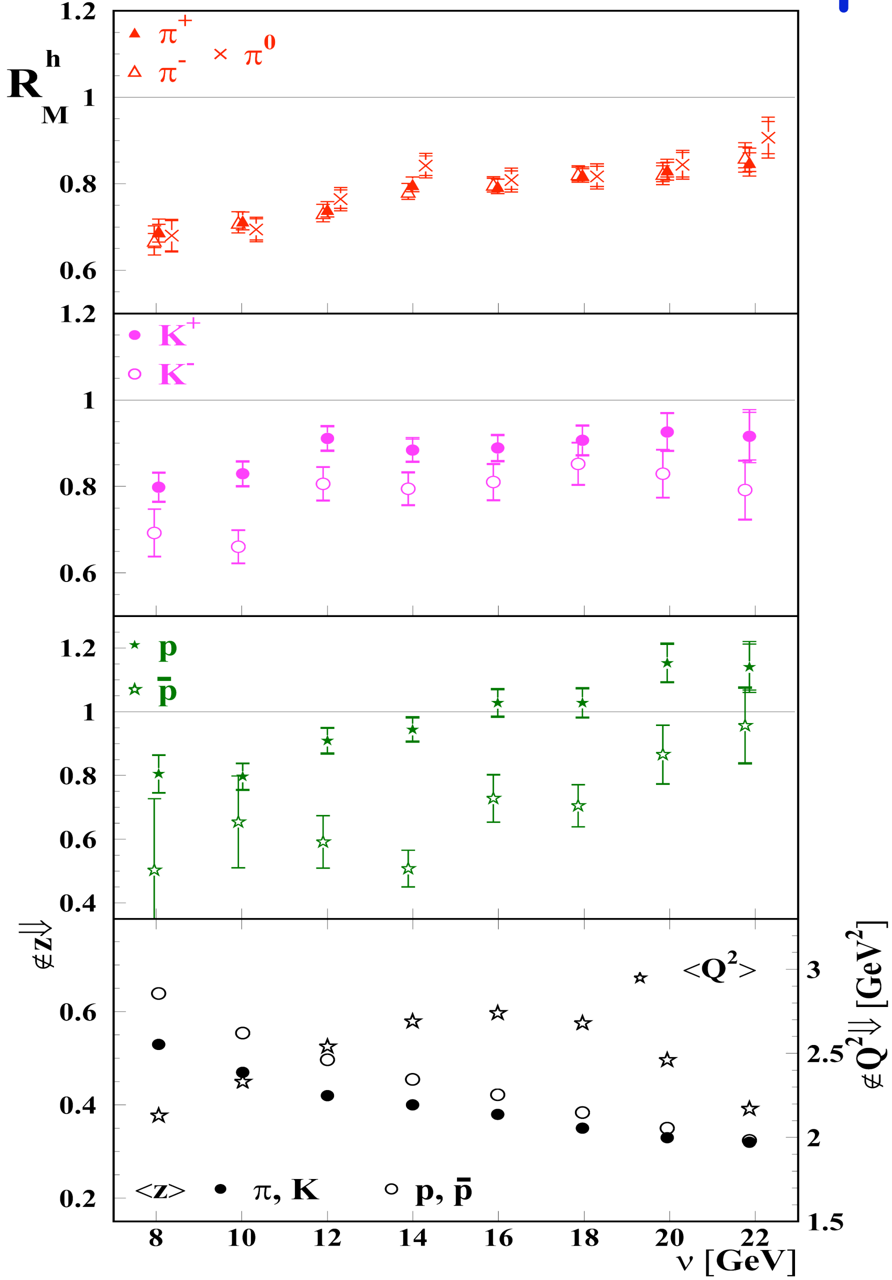
Hadron separation vs

HERMES, PLB 577 (2003) 37



Hadron separation vs ν

HERMES, PLB 577 (2003) 37



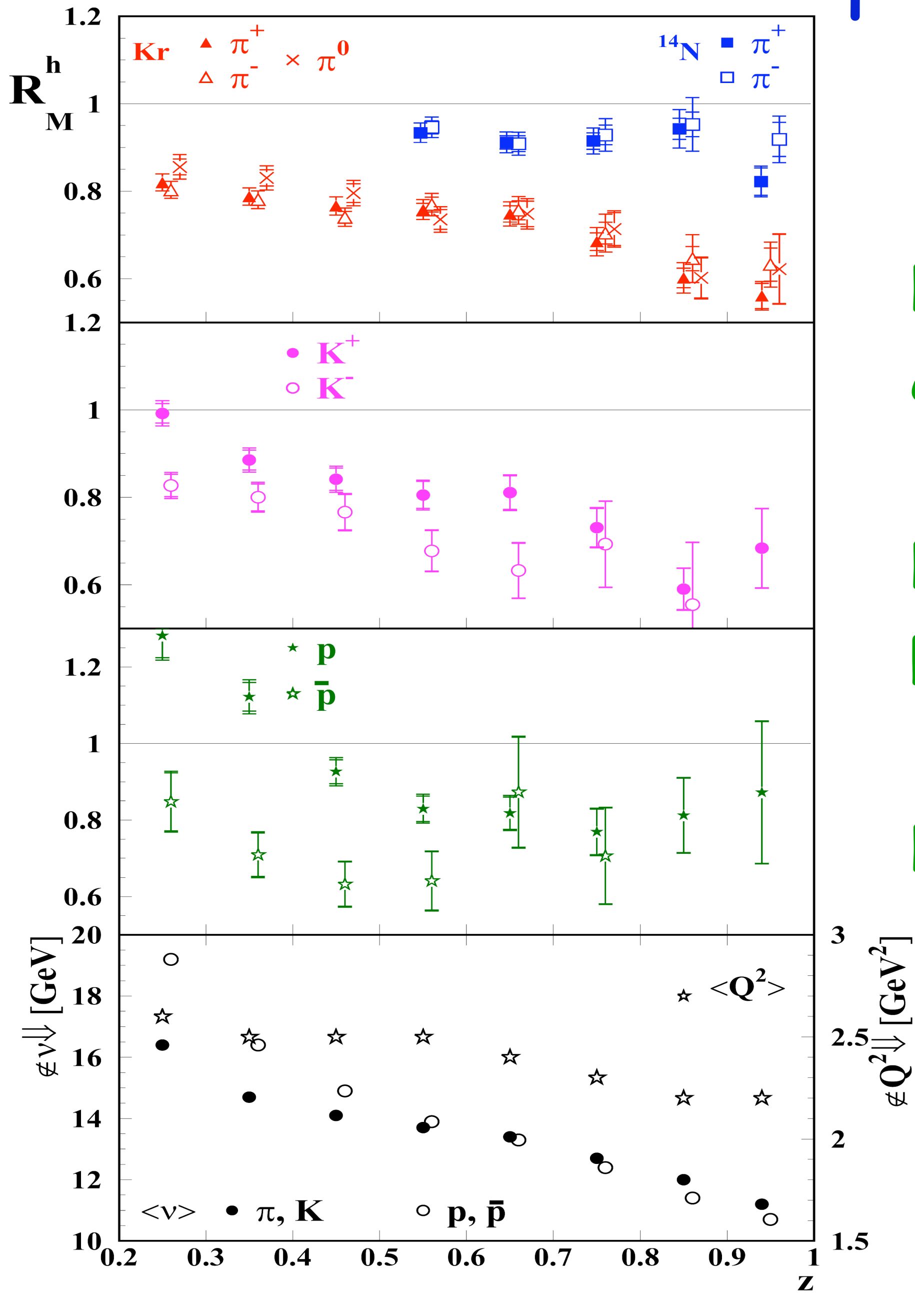
Experimental findings:

$\pi^+ = \pi^- = \pi^0 \sim K^-$

$K^+ > K^-$

$p > \bar{p}$, $p > \pi$, $p > K$

Hadron separation vs z



HERMES, PLB 577 (2003) 37

Different FF modification for *quark* and *anti-quark*

Different □$_h$ for mesons and baryons

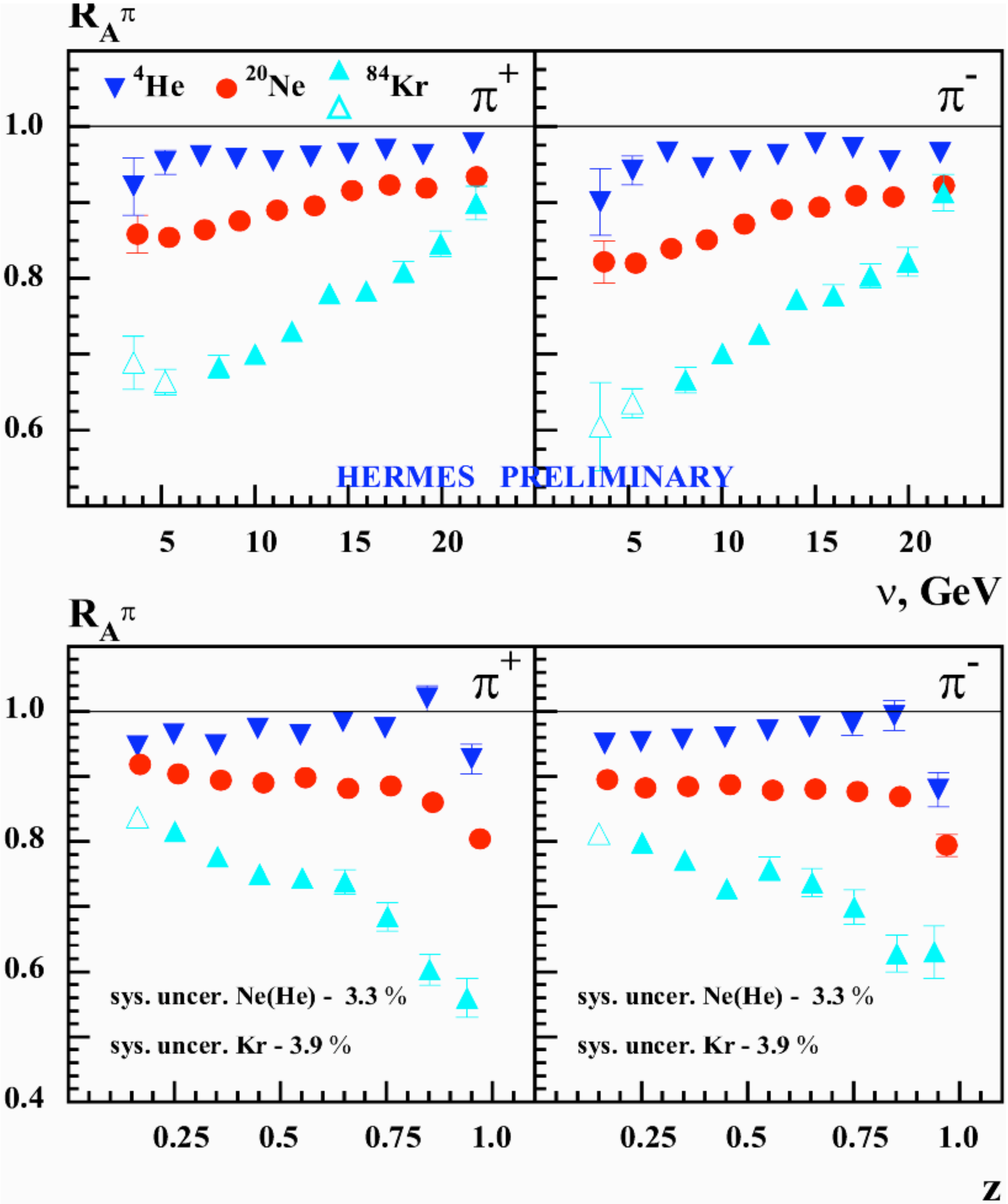
Different □$_h$:

□$_{□+}$ = □$_{□-}$ □ 20 mb

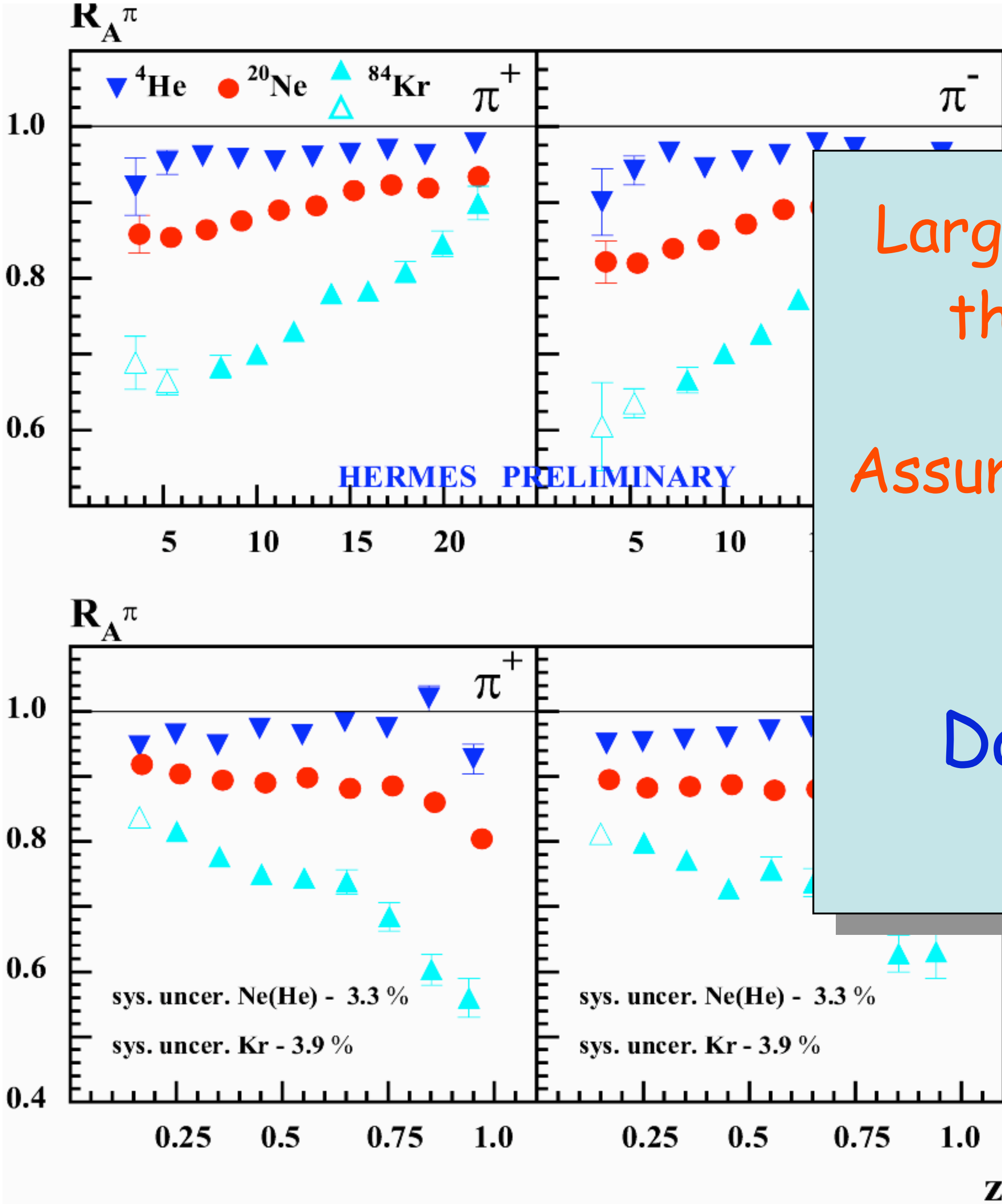
□$_{□+}$ □ 17 mb, □$_{□-}$□ 23 mb

□$_p$ □ 40 mb, □$_{p-}$ □ 60 mb

Nuclear Attenuation on He, Ne, Kr



Nuclear Attenuation on He, Ne, Kr



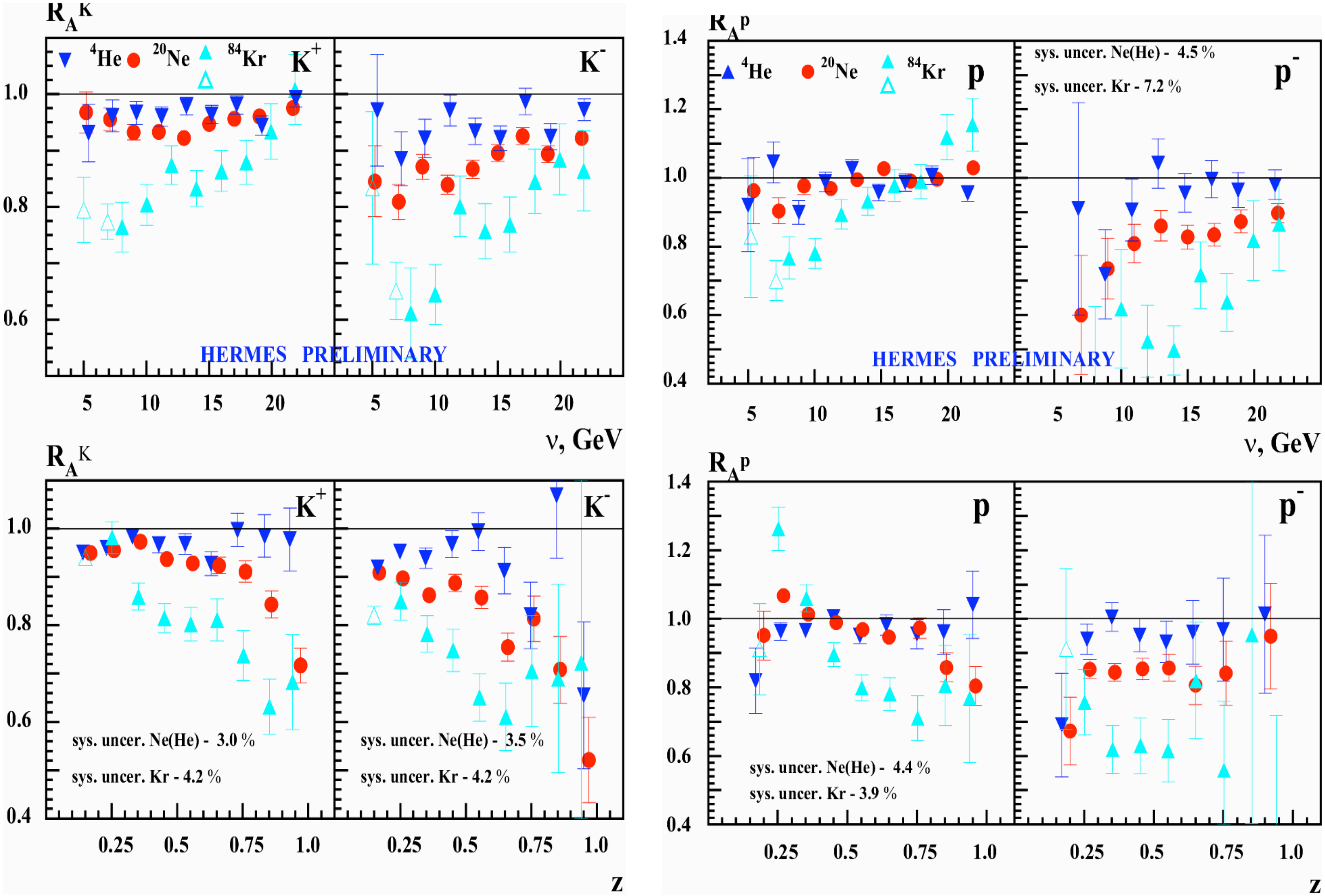
Large effect as a function of the atomic mass number

Assuming the dependence:

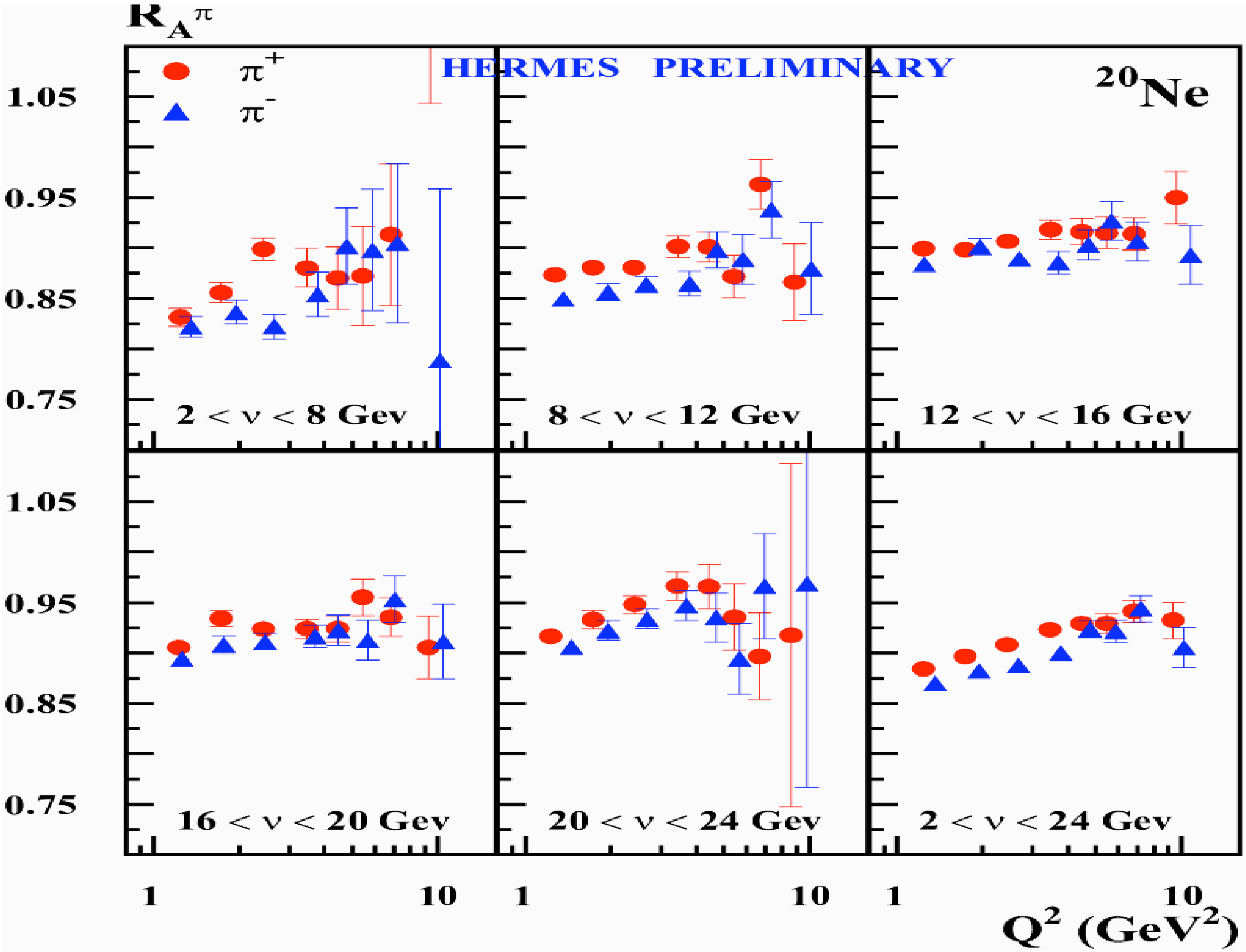
$A^{\alpha} = 1 - R^h_{att}$

Data suggest α~2/3

Nuclear Attenuation on He, Ne, Kr



Nuclear Attenuation vs Q^2



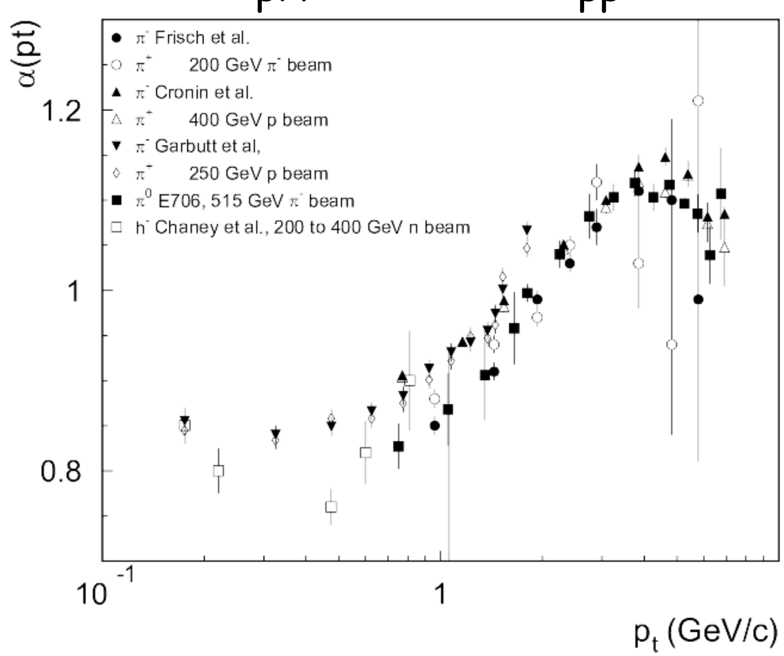
Dependence on Q^2:

stronger at small □, weaker at high □

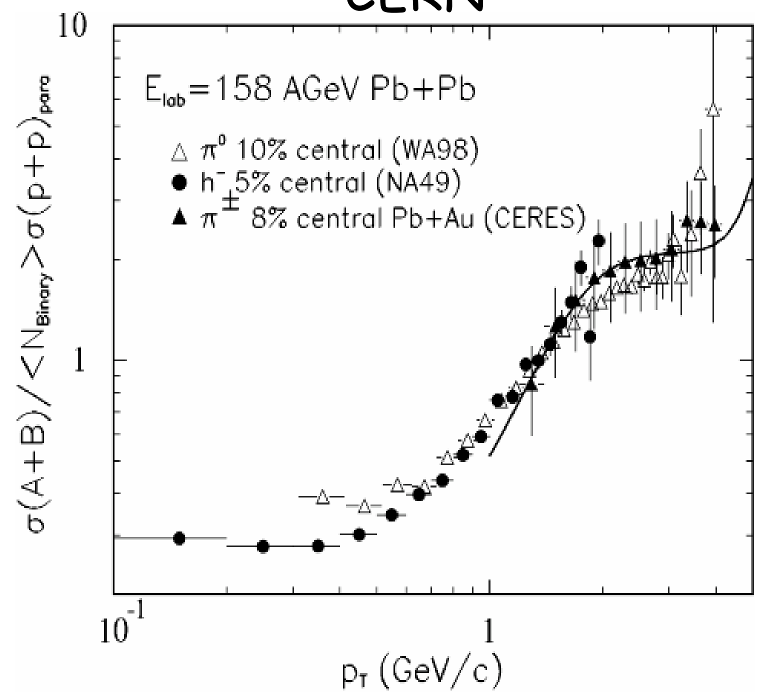
P_t dependence

In pA collisions the p gains extra transverse momentum due to random soft collisions. Partons enter the final hard process with extra kt (Cronin eff.)

$\sigma_{pA} = A^{\alpha(pt)}\sigma_{pp}$



CERN



Multiple parton scattering effects become dominant at p_t~ 1-2 GeV

P_t dependence

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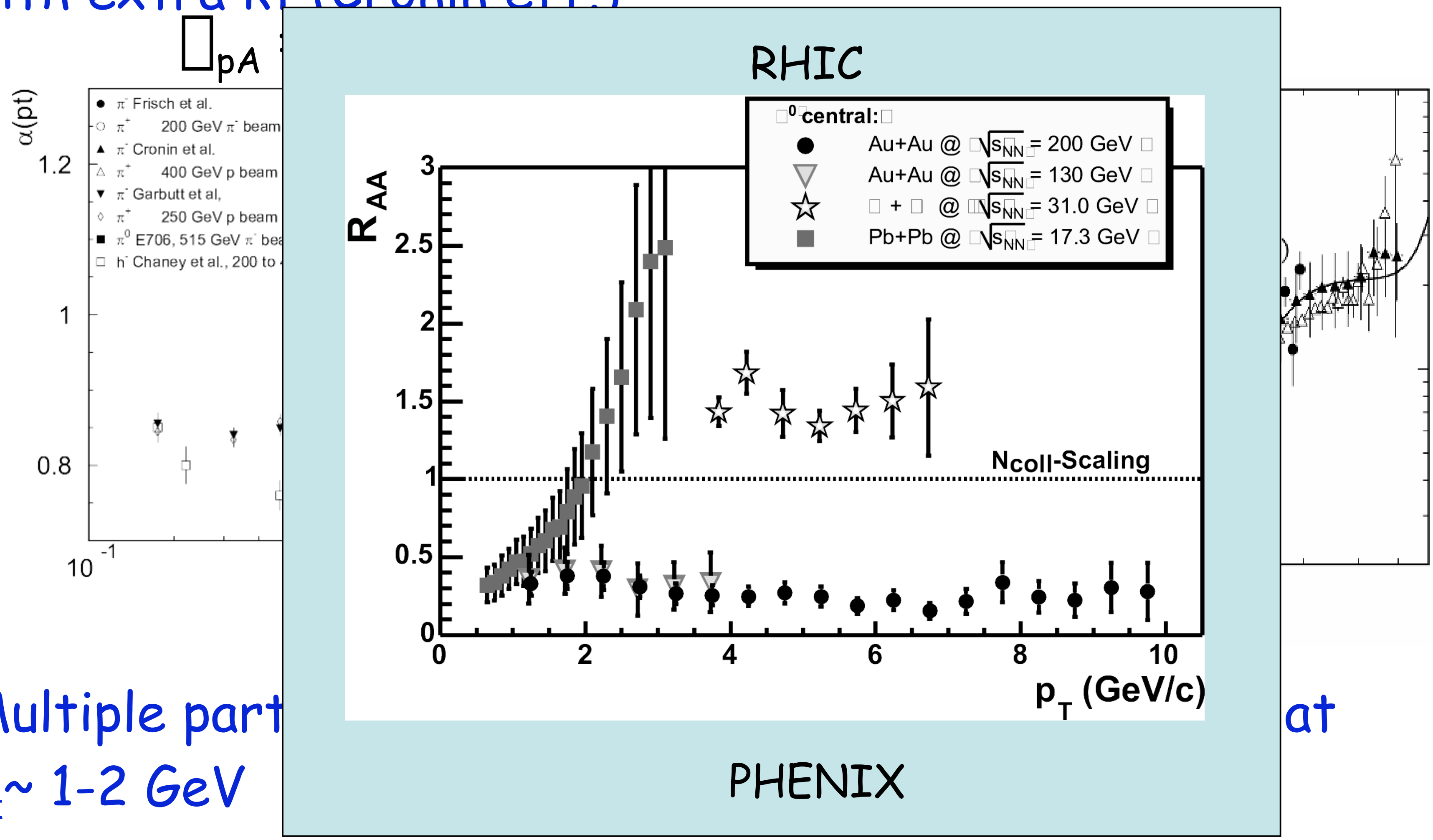
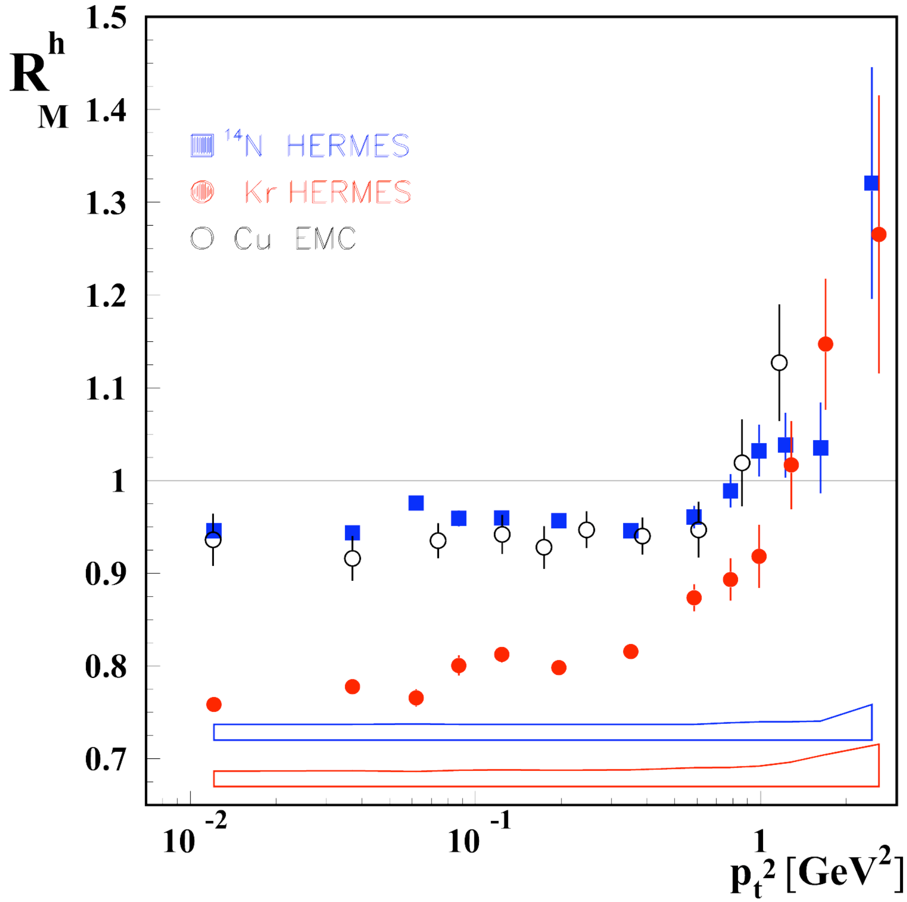


Multiple part … at

p_t~ 1-2 GeV

P_t dependence

In DIS neither multiple scattering of the incident particle nor interaction of its constituents complicate the interpretation

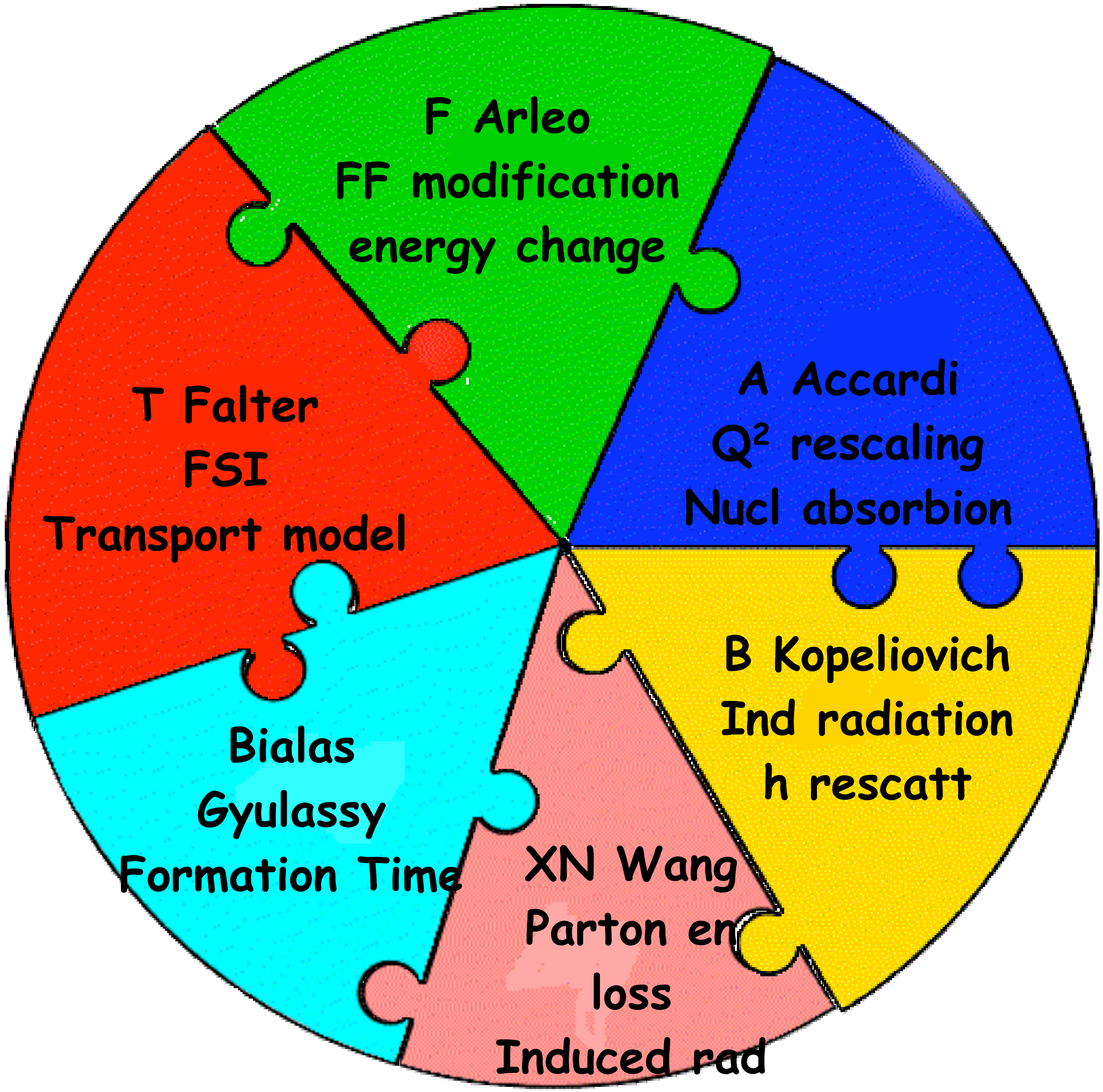


Data show a p_t enhancement similar to that observed in pA scattering (Cronin effect)

The hard component of incoherent parton scattering becomes dominant at p_t~1-2 GeV

Clean and reliable information on quark transport in 'cold' nuclear matter

Comparison with Theory



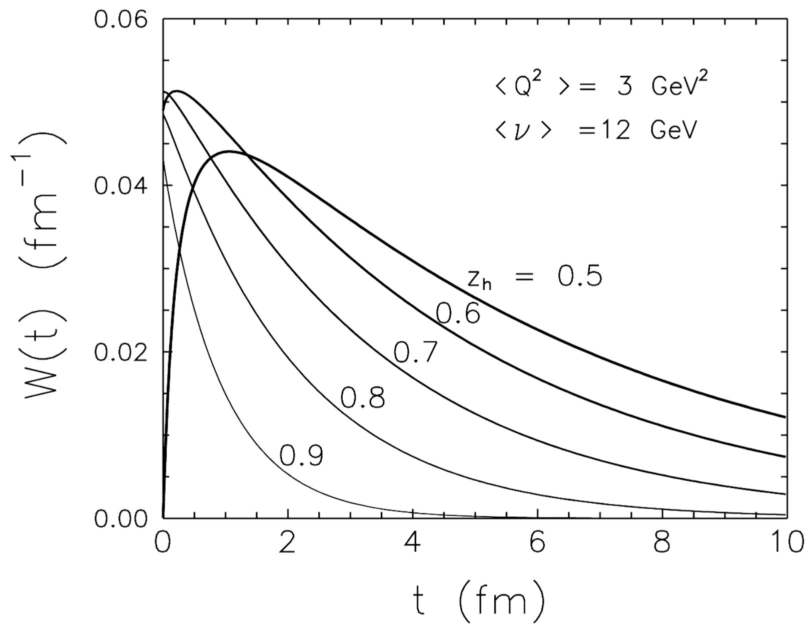
Gluon Bremsstrahlung

B.Kopeliovich et al.,
hep-ph/9511214
hep-ph/0311220

FF modification: Nuclear Suppression + Induced Radiation

- <u>Vacuum energy loss:</u> *$q \rightarrow gq'$.*
  (dE/dz ~2.5 GeV/fm by E772/E866 for DY on nuclei)
- <u>Energy loss induced by multiple interactions in the medium</u>
  (rising in p_t)
- <u>Color Transparency of the qq</u> (~$1/Q^2$)

$$\tilde{D}_{h/q}(z_h, Q^2) = \int_0 dt W(t, z_h, Q^2)$$



Gluon Bremsstrahlung

B.Kopeliovich et al.,
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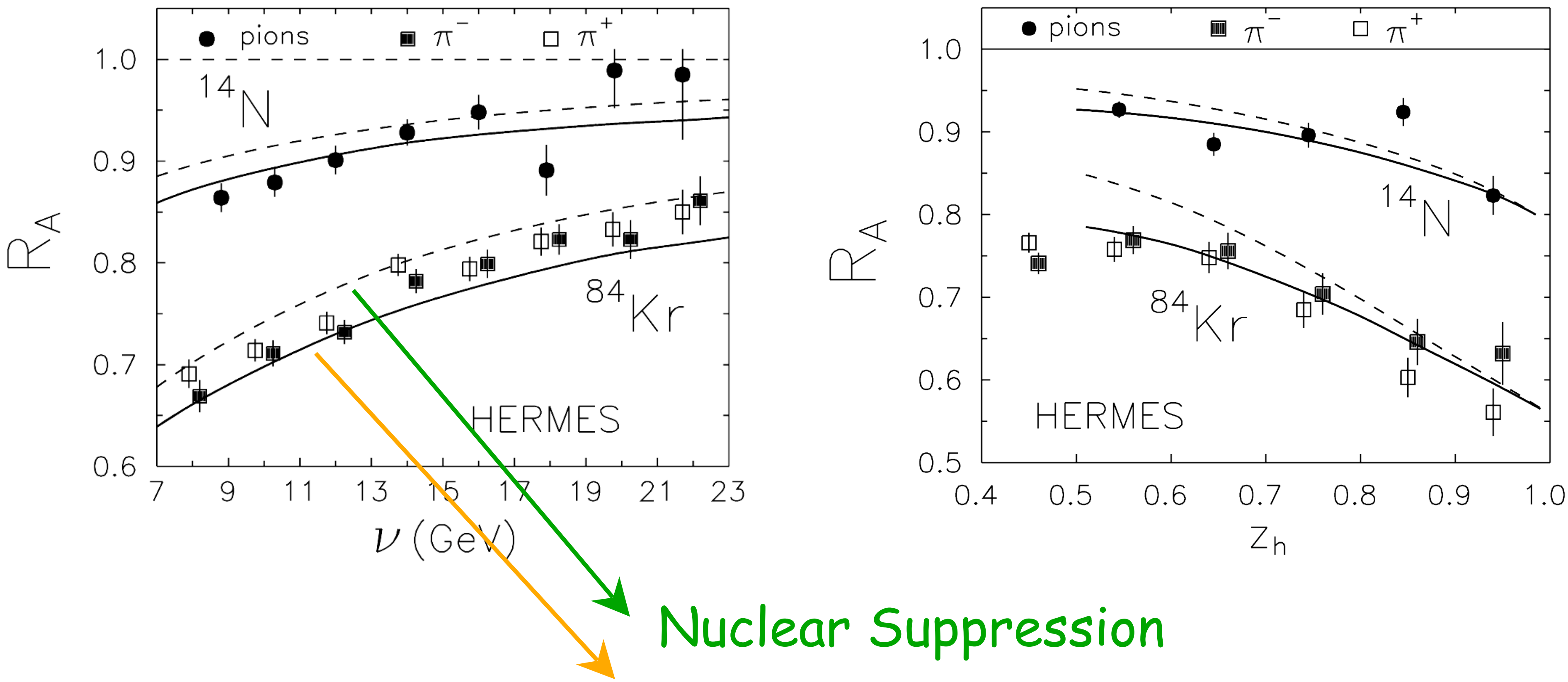


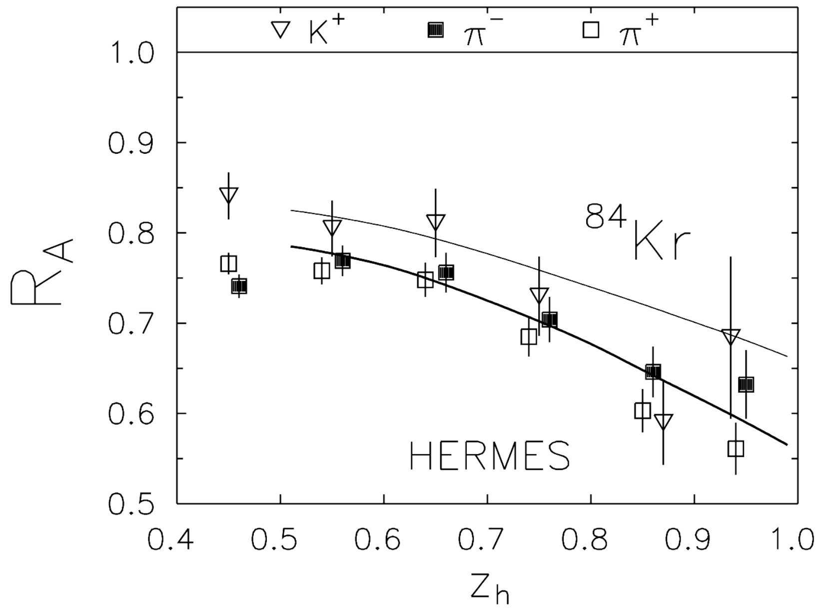
Nuclear Suppression

Nuclear Suppression + Induced Radiation

Fast pions are consistent with GB model (production length l_p $(1-z_h)$□$/Q^2$ vanish at $z_h \to 1$)

Gluon Bremsstrahlung

B.Kopeliovich et al.,
hep-ph/9511214
hep-ph/0311220

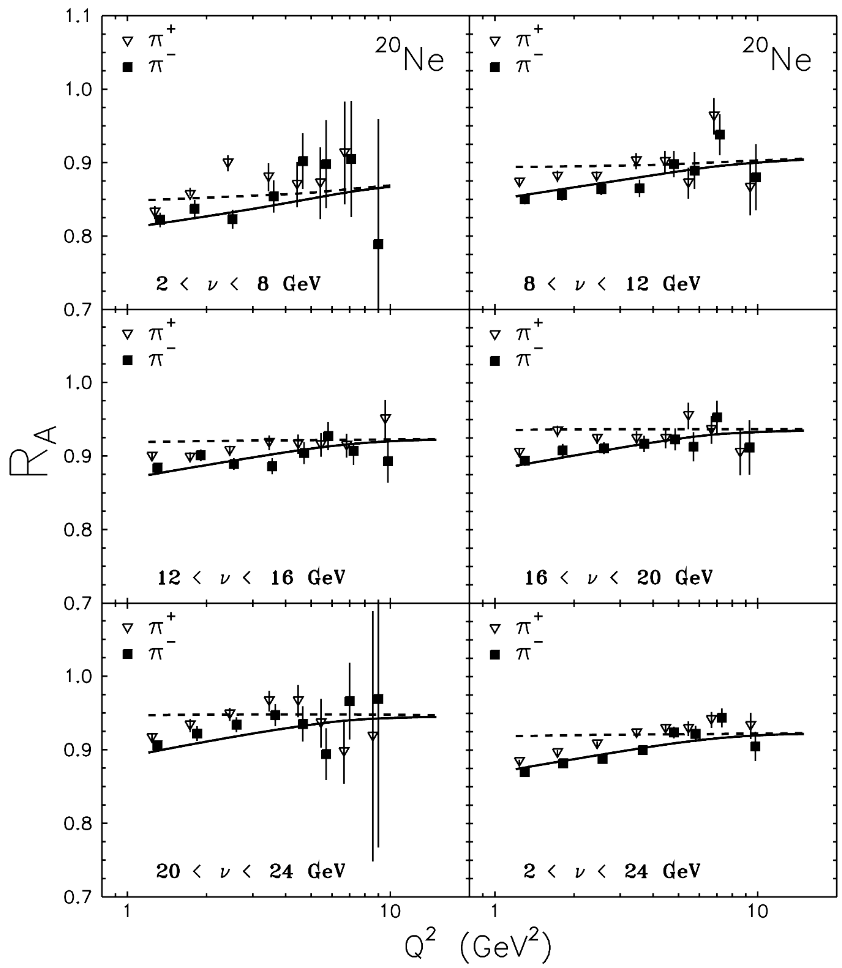


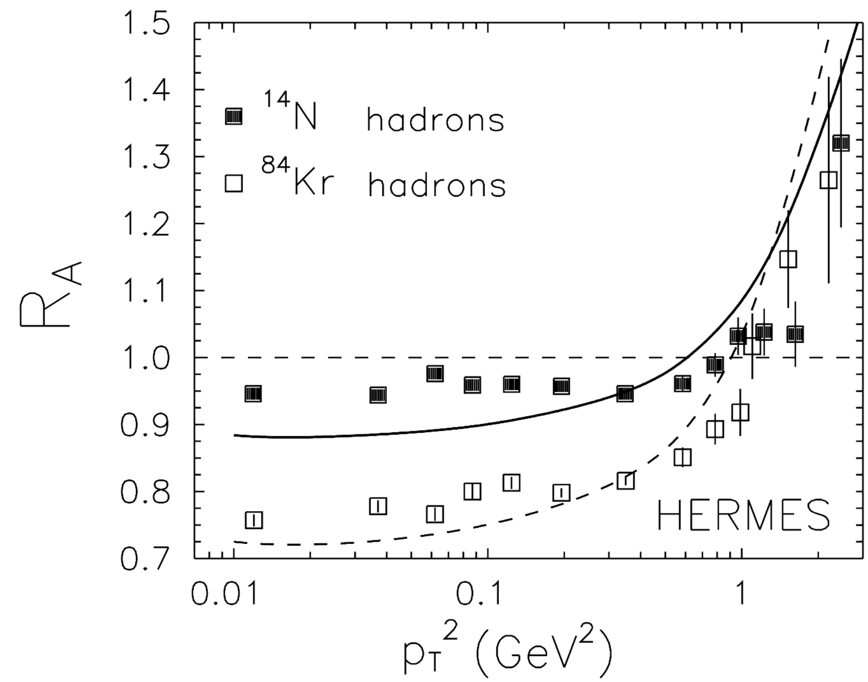
Only prediction for h containing target valence quark.

Good agreement also for K^+

Gluon Bremsstrahlung

B.Kopeliovich et al.,
hep-ph/9511214
hep-ph/0311220





Combined effects:

- pre-hadron shrinks at large Q^2
- larger nuclear transparency
- production lengths contracts

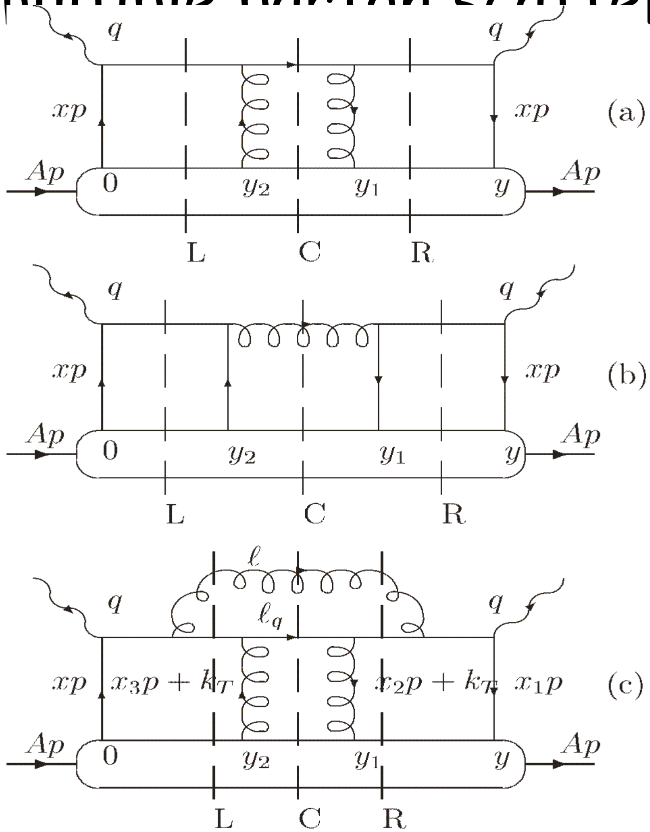
Good description;

Faster rise at high P_t ?

X.N.Wang et al.,
NPA696(2001)788
PRL89(2002)162301

FF modification

FF and their QCD evolution are described in the framework of multiple parton scattering (DGLAP).



Rescattering without gluon radiation: p_t-broadening.

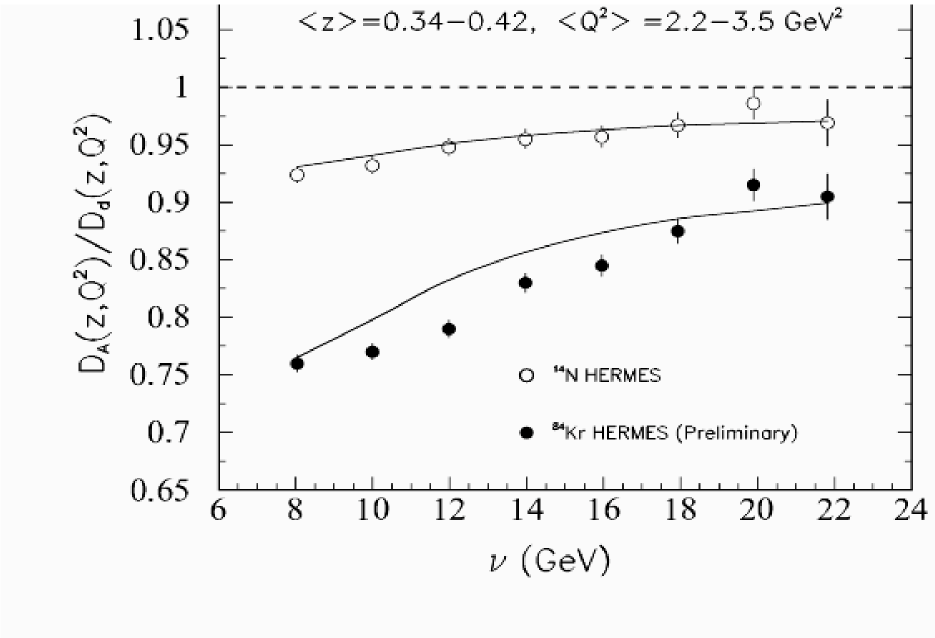
Rescattering with another *q* : mix of *q* and *g* FF.

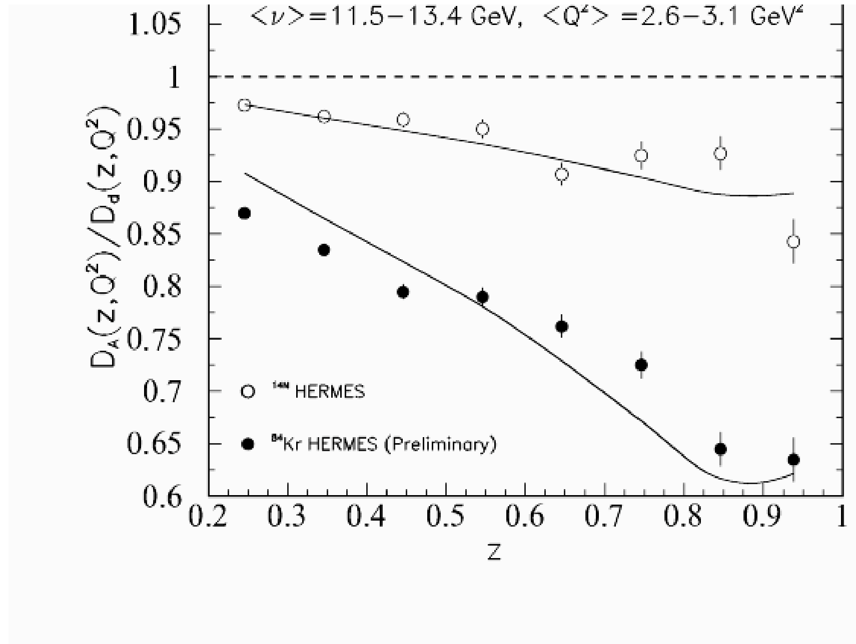
g-rescattering including *g*-radiation: dominant contribution in QCD evolution of FF.

- The emitted *g* and the leading *q* propagate coherently Landau-Pomeranchuk-Midgal interference effects.
- Different modification of quark and antiquark FF.

FF modification
(parton energy loss)

X.N.Wang et al.,
NPA696(2001)788
PRL89(2002)162301





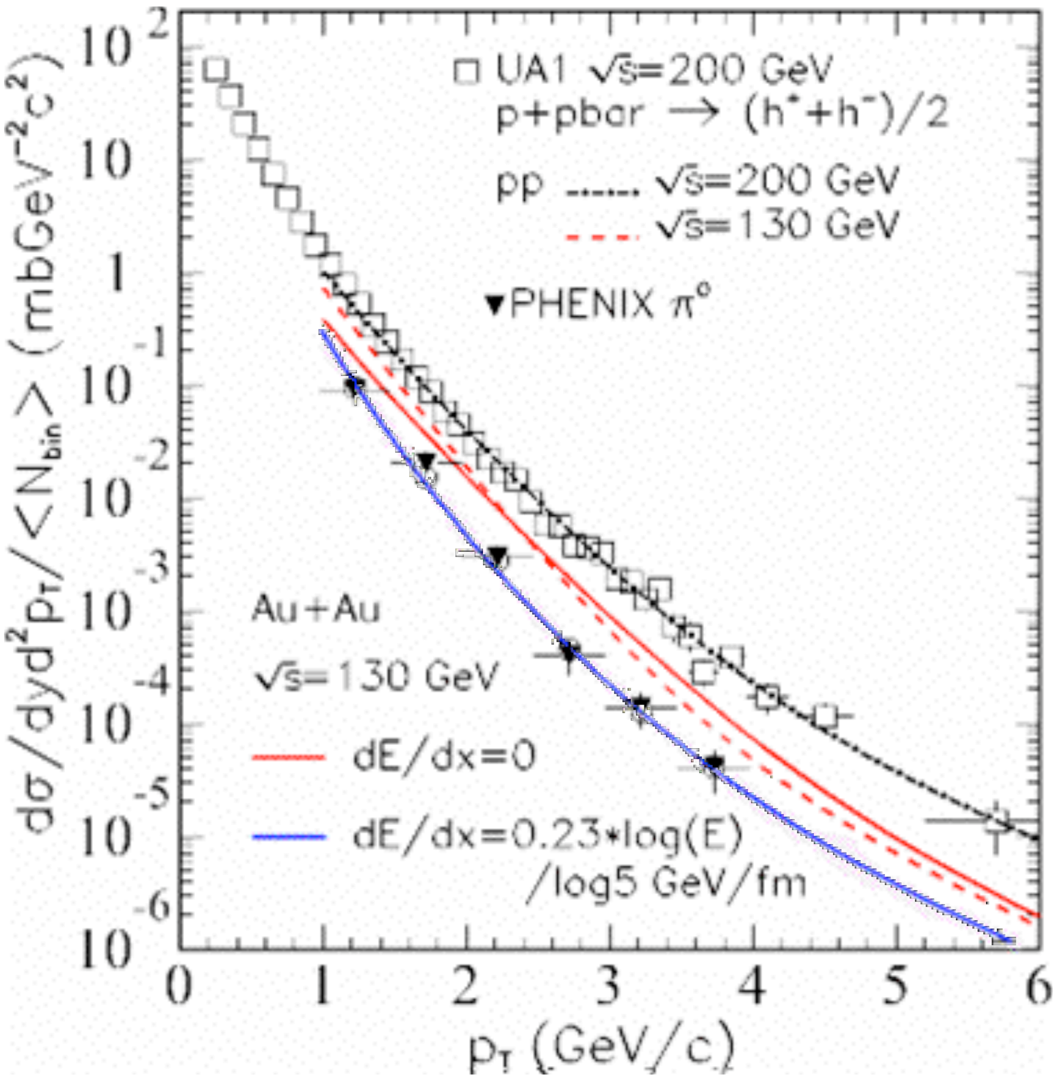
- 1 free parameter tuned on ^{14}N (quark-gluon correlation strength inside nuclei)

- dE/dx for HERMES → dE/dx for PHENIX (Au)

Gluon Density

X.N.Wang et al.,
NPA696(2001)788
PRL89(2002)162301

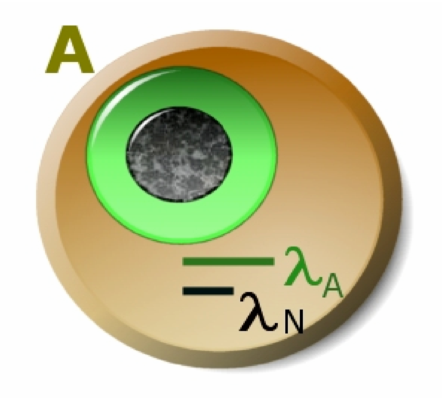
$\square E_{exp} \square\ \square E_{sta}(2\square_0/R_A) \quad 2\square_0 R_A \square_0$



- Cold <--> Hot nuclear matter correlation
- Gluon density in Au+Au~15 times higher than in cold matter

Rescaling + Absorption Model

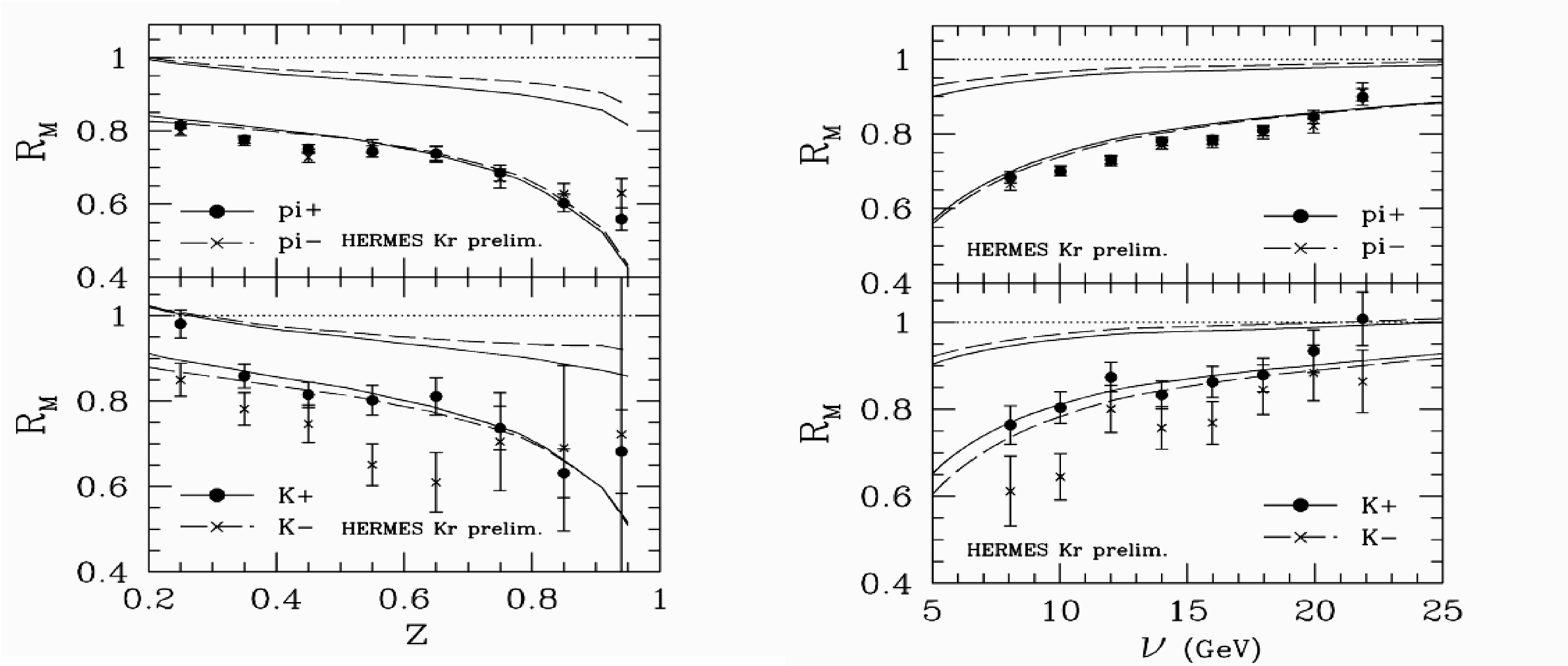
A.Accardi et al., NPA720(2003)131



$$\lambda_A > \lambda_N \,; \qquad \xi_A(Q^2) = \left(\frac{\lambda_N^2}{\lambda_A^2}\right)^{\frac{\alpha_s(\mu_A^2)}{\alpha_s(Q^2)}}$$

$$q_f^A(x,Q^2) = q_f(x,\xi_A(Q^2)Q^2)$$

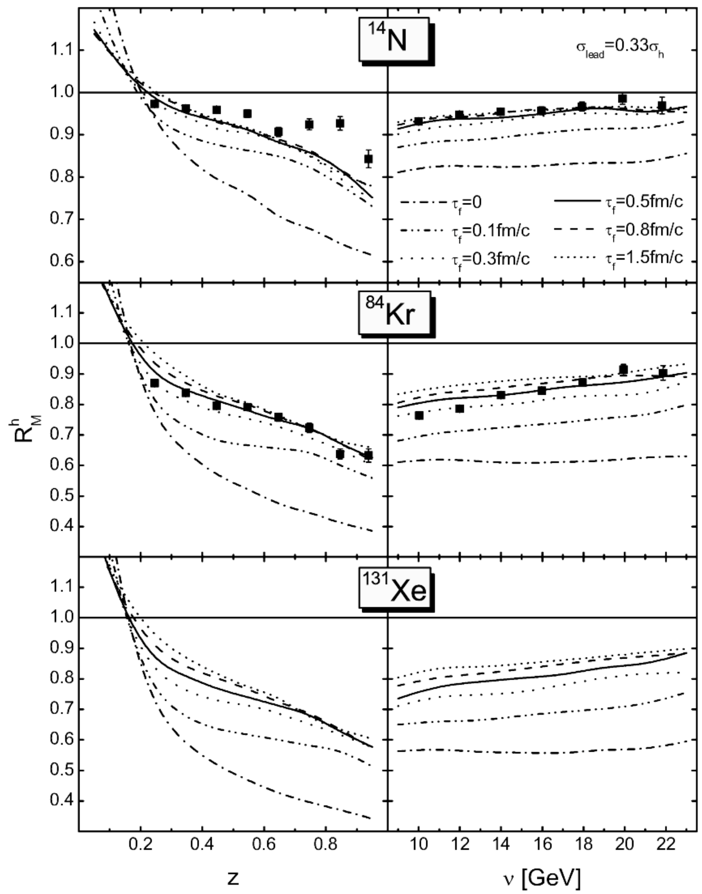
$$D_f^{h|A}(z,Q^2) = D_f^h(z,\xi_A(Q^2)Q^2)$$

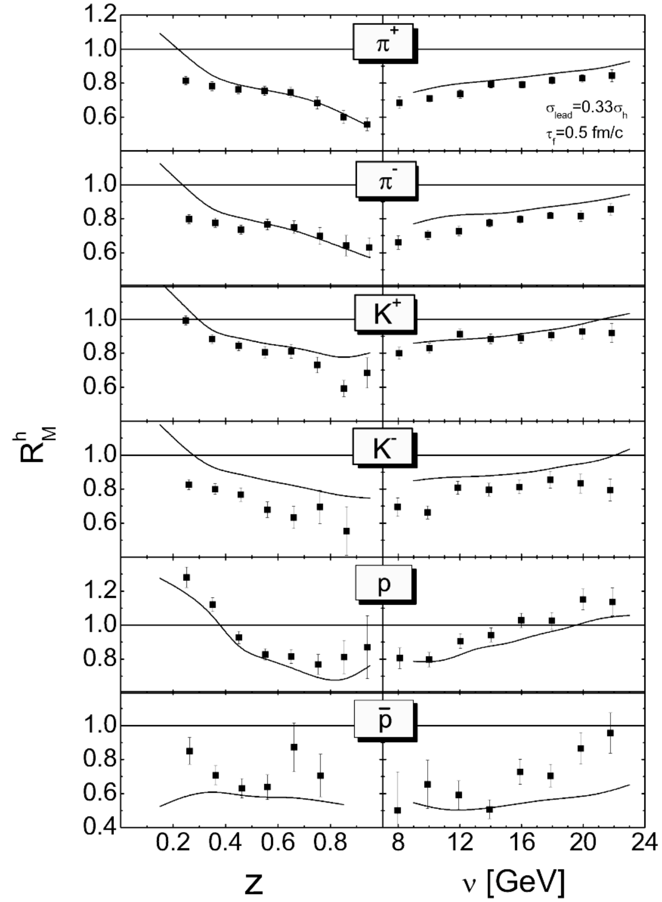


Nice agreement for p+, p-, K+ with Q^2-rescaling + nuclear absorption (lower curves).

(Pre-)Hadron FSI and formation times

T.Falter et al., nucl-th/0303011



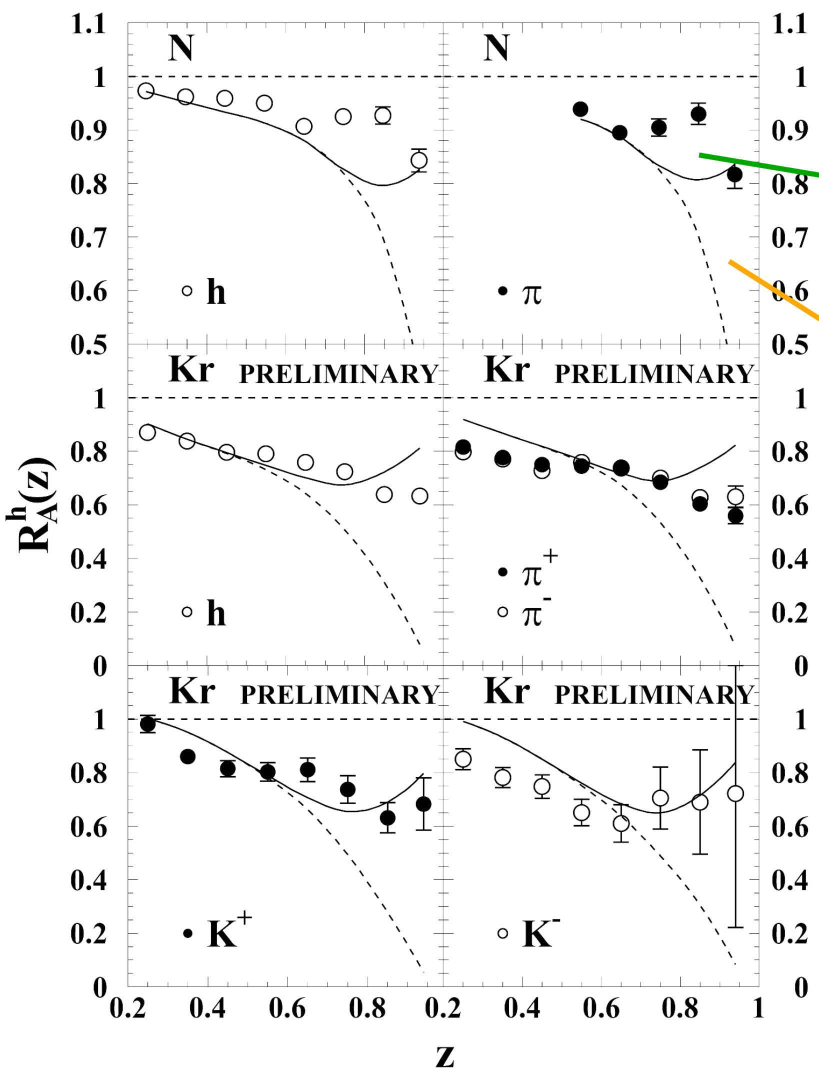


R_M is very sensitive to the σ_{pre-h} ; ($\sigma_{pre-h}=0.33\ \sigma_h$)

$\tau_f>0.5$ fm/c compatible with data

FF modification + transport coef.

F.Arleo et al., NPA715(2003)899



With formation time effect

Without formation time effect

- Energy loss taken into account
- Soft gluons radiated in the dense QCD medium (transport coefficient calculated from DY)
- Nice agreement with both

Disentangling absorption and induced energy loss

In case of absorption, suppression for double-hadron production is SMALL compared to single-hadron production

$$R_2 = \frac{\left(\frac{R^{2h}}{R^{1h}}\right)_A}{\left(\frac{R^{2h}}{R^{1h}}\right)_D}$$

Could it be too naïve ?

R_2 depends on:

- hadron production length
- local nuclear density
- absorption cross section
- P_t, z_1, z_2, …

Disentangling absorption and induced energy loss

Preliminary R_2 calculated for Kr/D and N/D:

- $\nu > 7$ GeV, $E_h > 1.4$ GeV, $z_{leading} > 0.5$
- opposite charges neglected (rank-2)

$$R_2(Kr/D) = 0.929 \pm 0.025$$

$$R_2(N/D) = 0.946 \pm 0.018$$

Results from STAR show jet suppression is due to FSI (energy loss). No contribution from absorption …

Disentangling absorption and induced energy loss

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$$R_2(N/D) = 0.946 \pm 0.018$$

Results from STAR show jet suppression is due to FSI (energy loss). No contribution from absorption … high Pt events, different z_h distributions. It's difficult to compare HERMES-RHIC … for the moment.

Conclusions

- Significant hadron suppression, in a wide region of the kinematical plane, measured for ^{4}He, ^{14}N, ^{20}Ne, ^{84}Kr
- First observation of hadron-type dependence of the attenuation: $□^{+}$, $□^{-}$, $□^{0}$, K^{+}, K^{-}, p, $\bar{p}$
- Large atomic mass number dependence
- The Cronin effect has been observed: transition occurs at P_t~1 GeV
- Large final hadron re-interaction is unlikely
- Pre-hadronic re-interaction and/or partonic energy loss ?

Outlook: Disentangle between □ and z dependence
P_t broadening for different hadrons
Double/Single-hadron ratio

Pasquale Di Nezza
INFN Frascati

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GOAL

To obtain unambiguous information on hadron formation and transport in Cold Nuclear Matter

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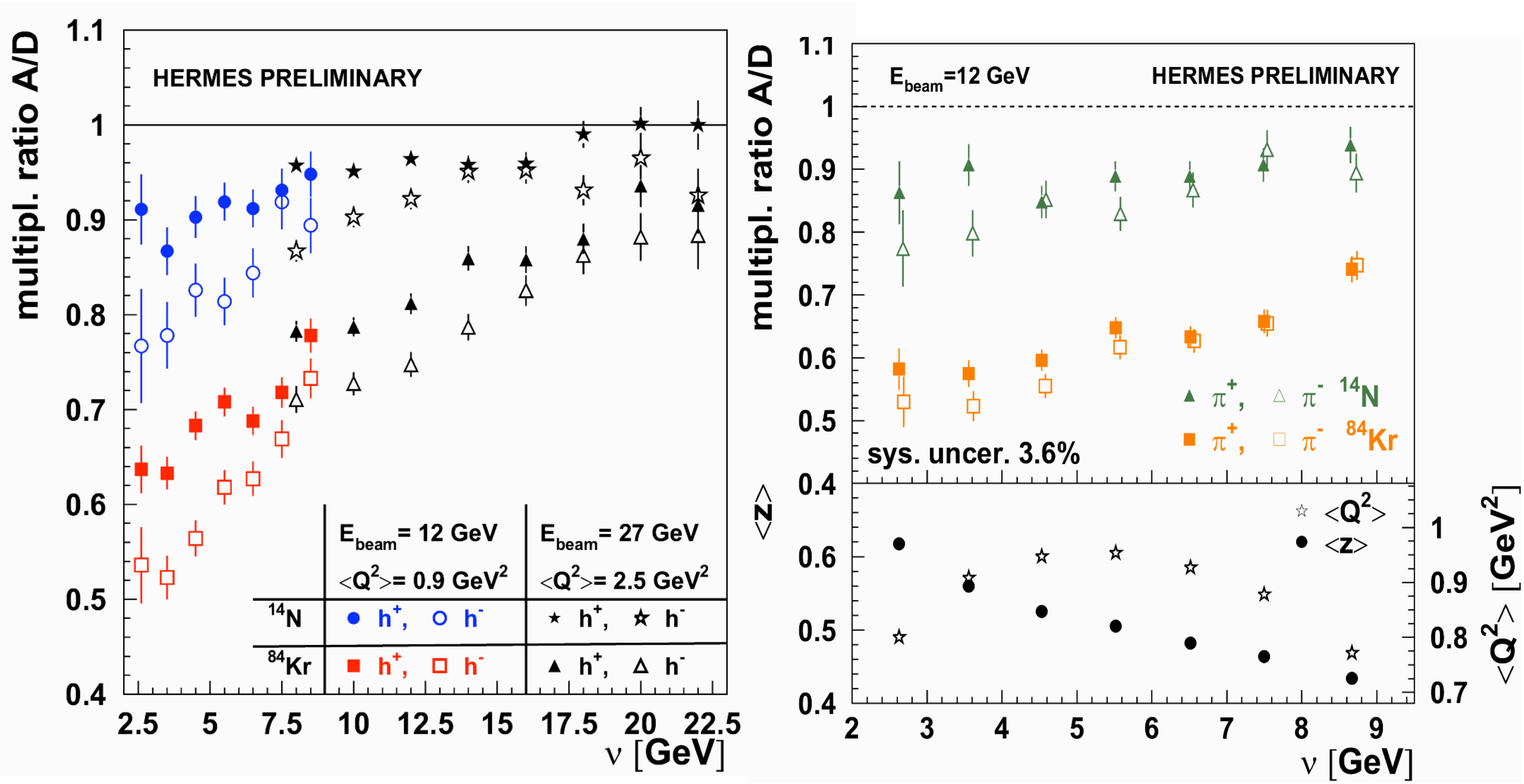
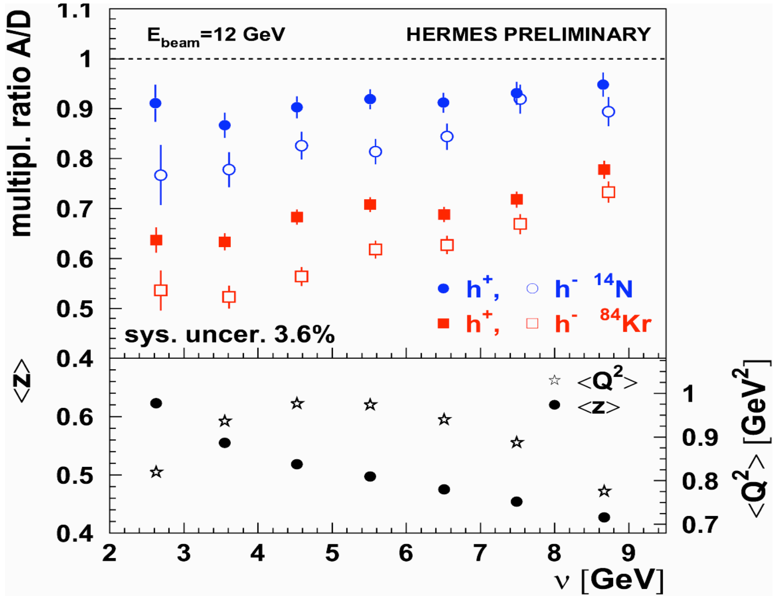
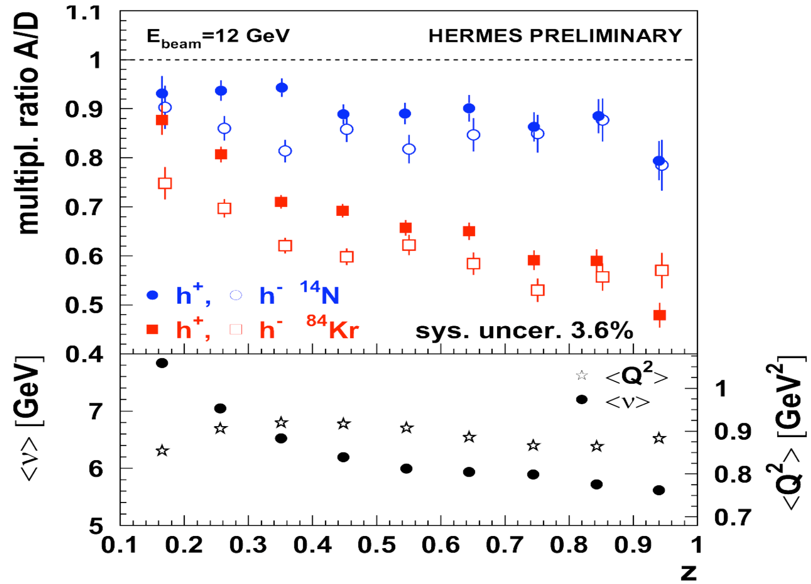
Double/Single-hadron ratio

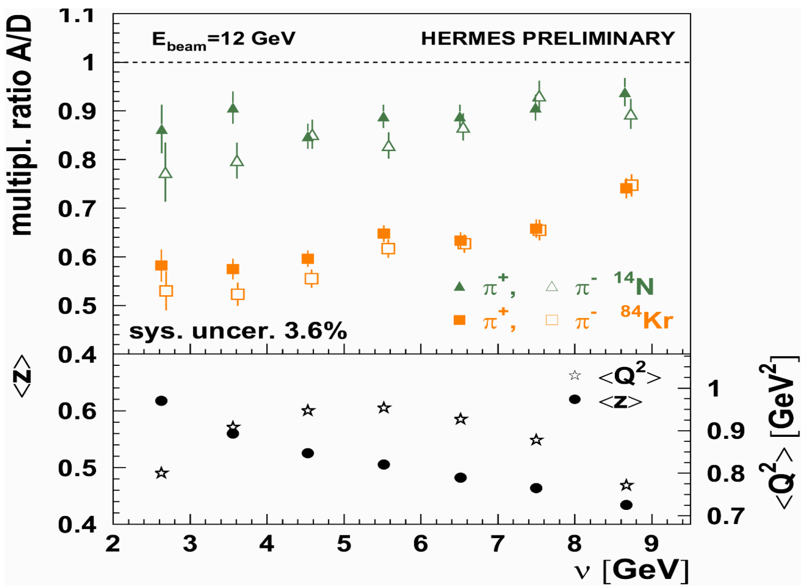
Hadrons and Pions @ E_{beam}=12 & 27 GeV

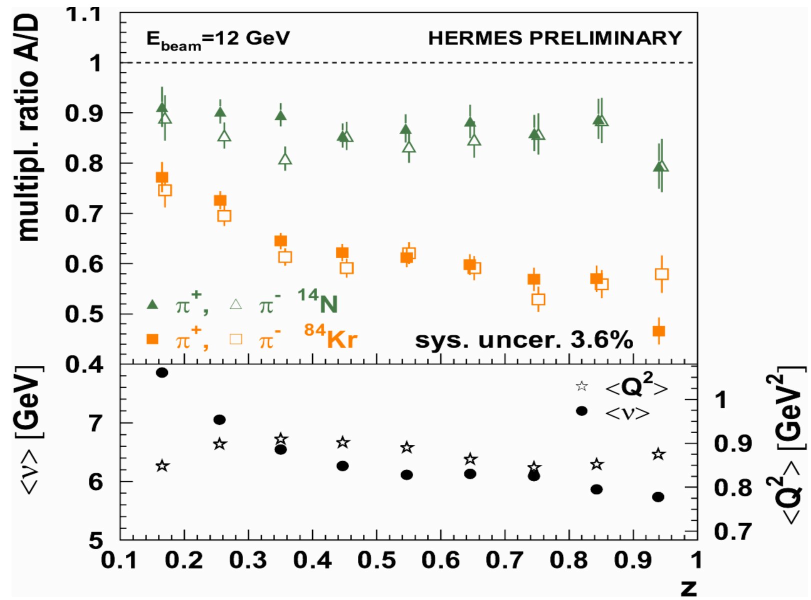
Extension of the range down to 2 GeV

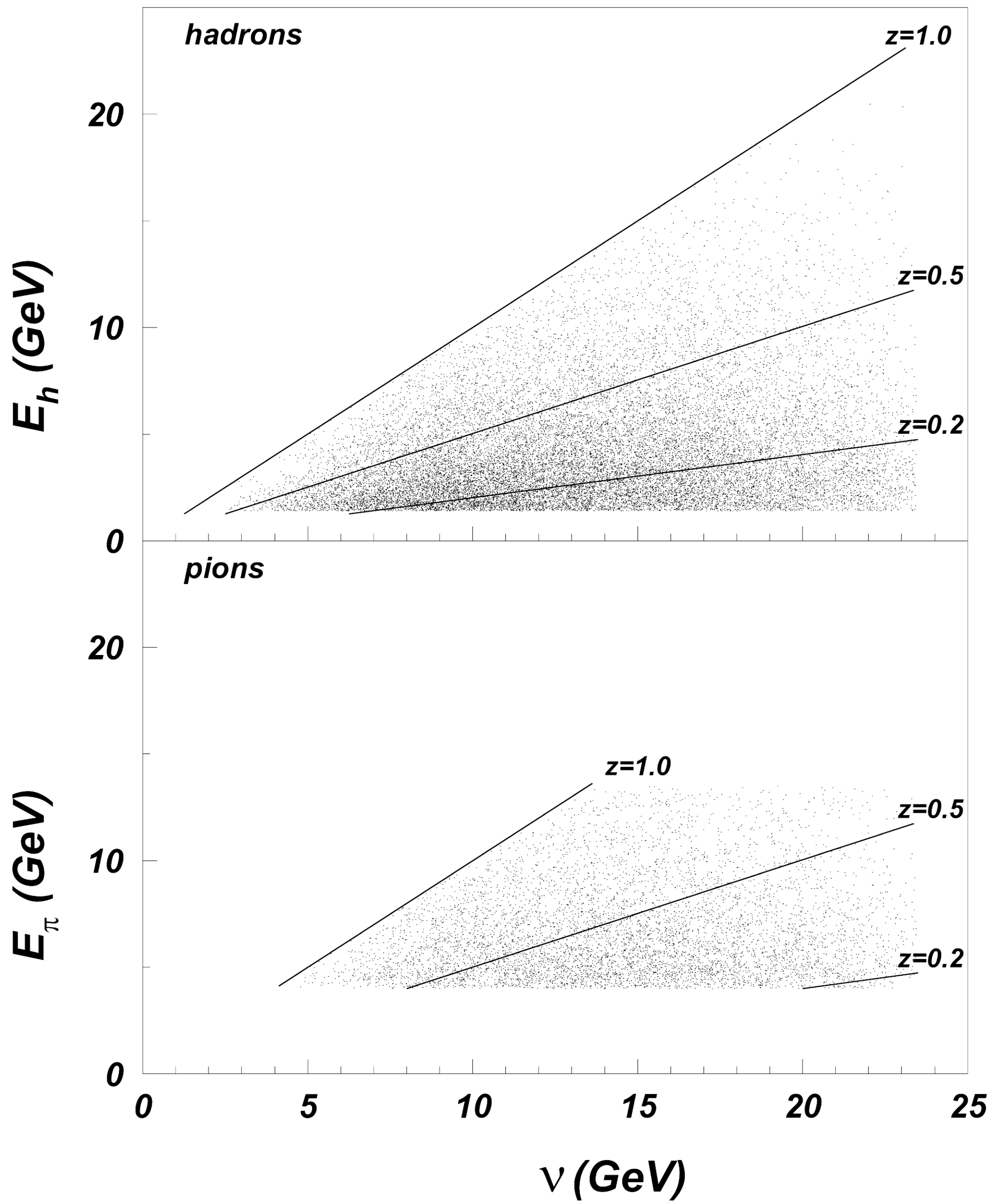



E_beam=12 GeV
HERMES PRELIMINARY
multipl. ratio A/D
h+, h- 14N
h+, h- 84Kr
sys. uncer. 3.6%
<z>
<Q2>
<Q2> [GeV2]
ν [GeV]


E_beam=12 GeV
HERMES PRELIMINARY
multipl. ratio A/D
h+, h- 14N
h+, h- 84Kr
sys. uncer. 3.6%
<ν> [GeV]
<Q2>
<ν>
<Q2> [GeV2]
z


E_beam=12 GeV
HERMES PRELIMINARY
multipl. ratio A/D
π+, π- 14N
π+, π- 84Kr
sys. uncer. 3.6%
<z>
<Q2>
<Q2> [GeV2]
ν [GeV]


E_beam=12 GeV
HERMES PRELIMINARY
multipl. ratio A/D
π+, π- 14N
π+, π- 84Kr
sys. uncer. 3.6%
<ν> [GeV]
<Q2>
<ν>
<Q2> [GeV2]
z



hadrons
z=1.0
z=0.5
z=0.2
20
10
0
E_h (GeV)
pions
z=1.0
z=0.5
z=0.2
20
10
0
E_π (GeV)
0
5
10
15
20
25
ν (GeV)